

*Searching for Heavy Leptophilic Z' : from **Muon Collider** to **Gravitational Waves***

Si Wang

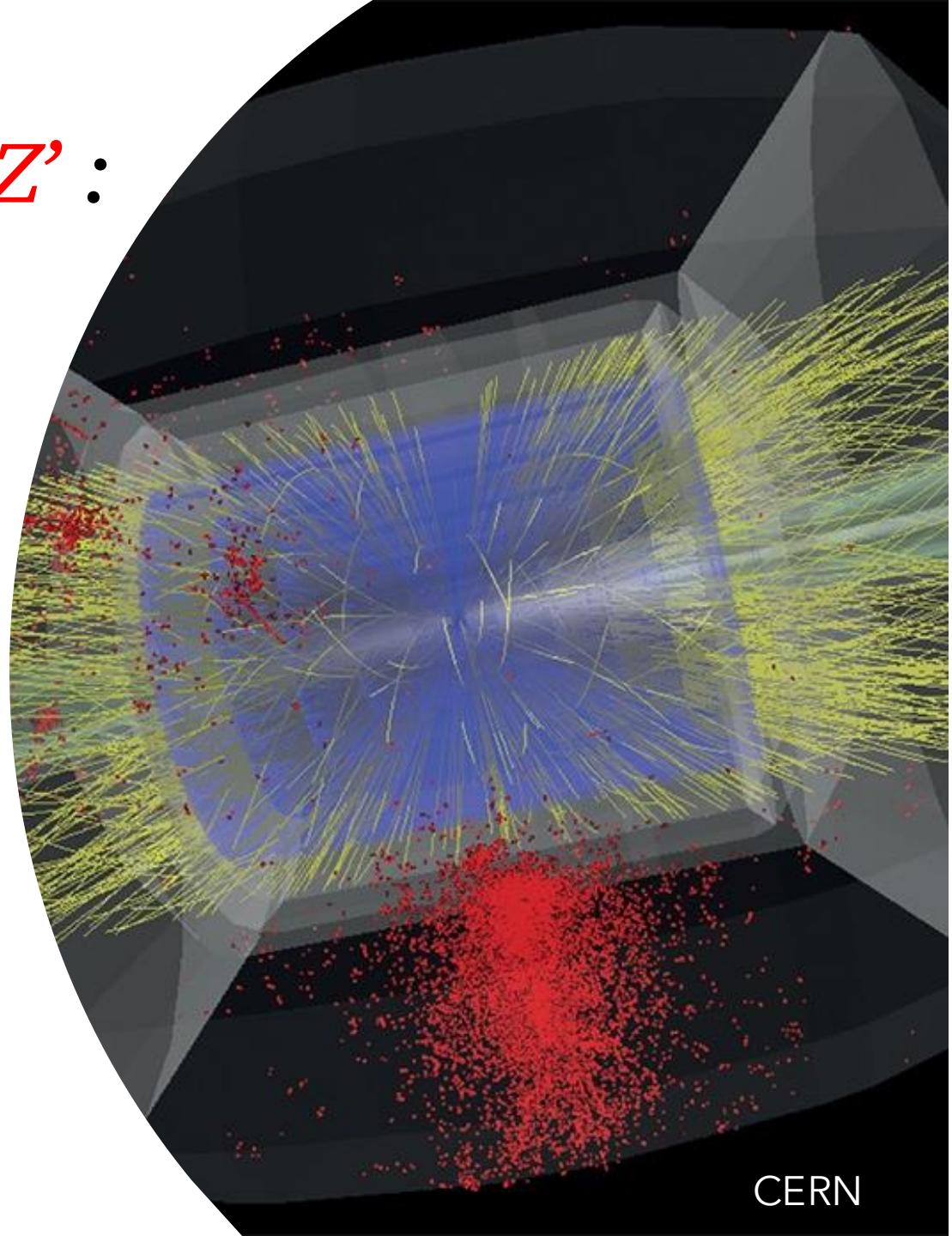
University of Pittsburgh

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Collaborators:

A. Dasgupta, P.S. B. Dev, T. Han, R. Padhan, K. Xie

arXiv: 2308.12804



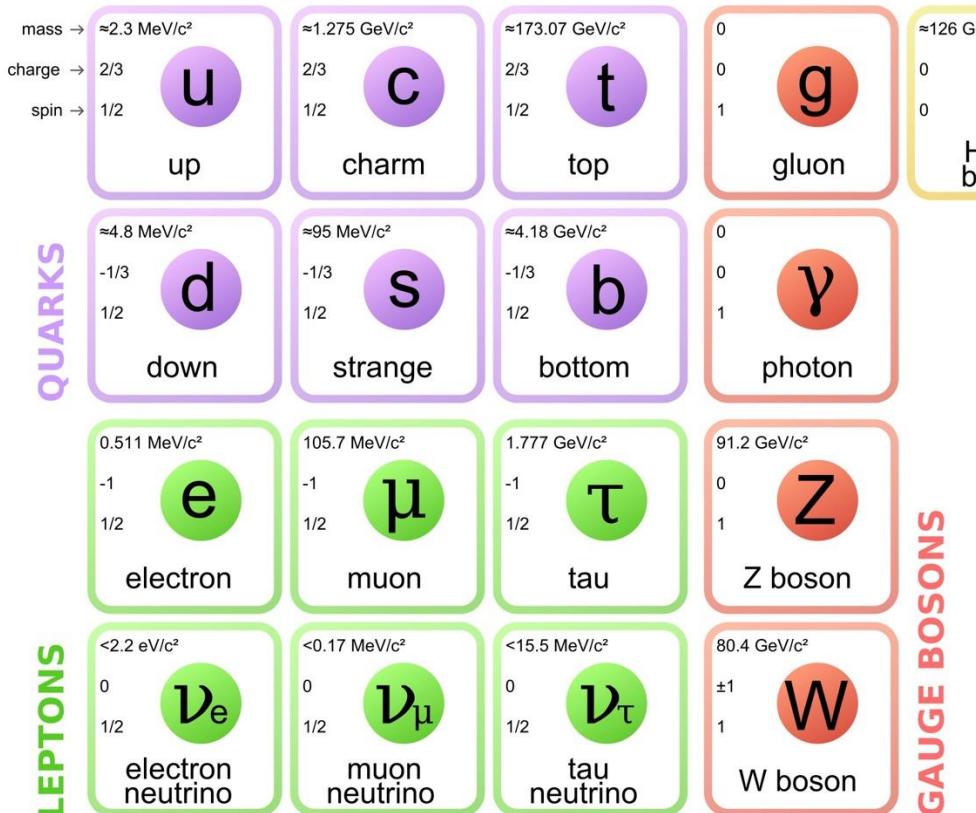
CERN

Outline

- Gauge U(1) Model and Z' particle
- Muon Collider Search
- Gravitational Waves from first order phase transition

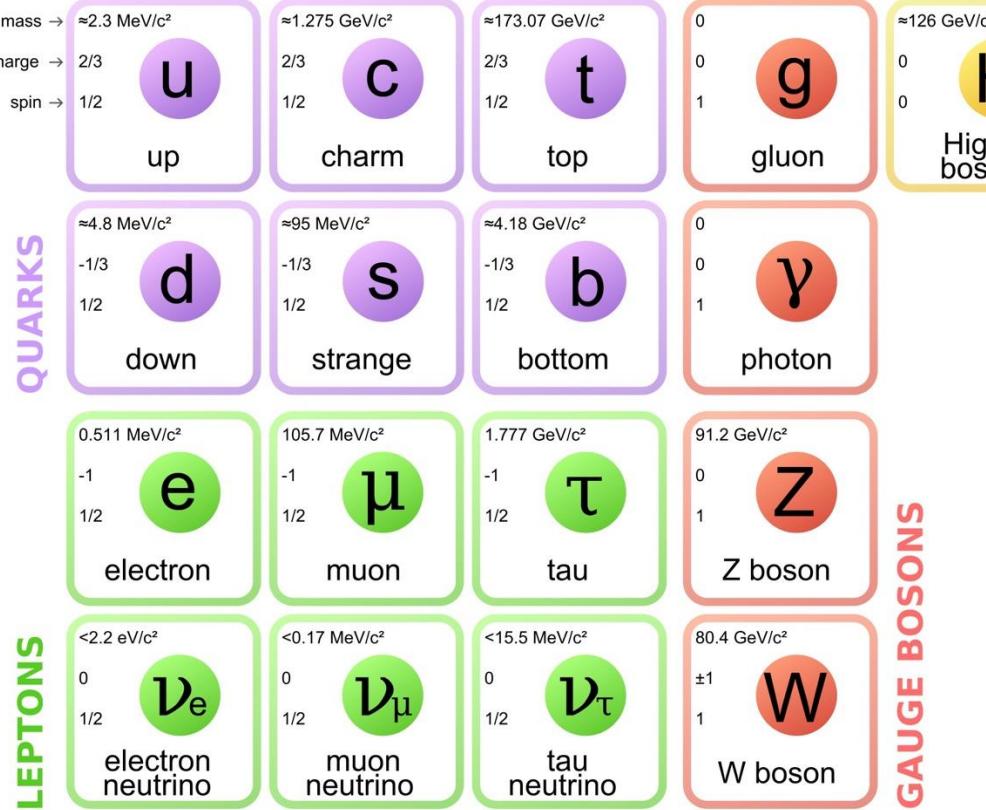


The Standard Model



(image credit: quantum diaries)

The Standard Model



(image credit: quantum diaries)

The Success of Standard Model:

- Prediction and discovery of W, Z, t, H
- Precision Measurement of Electroweak

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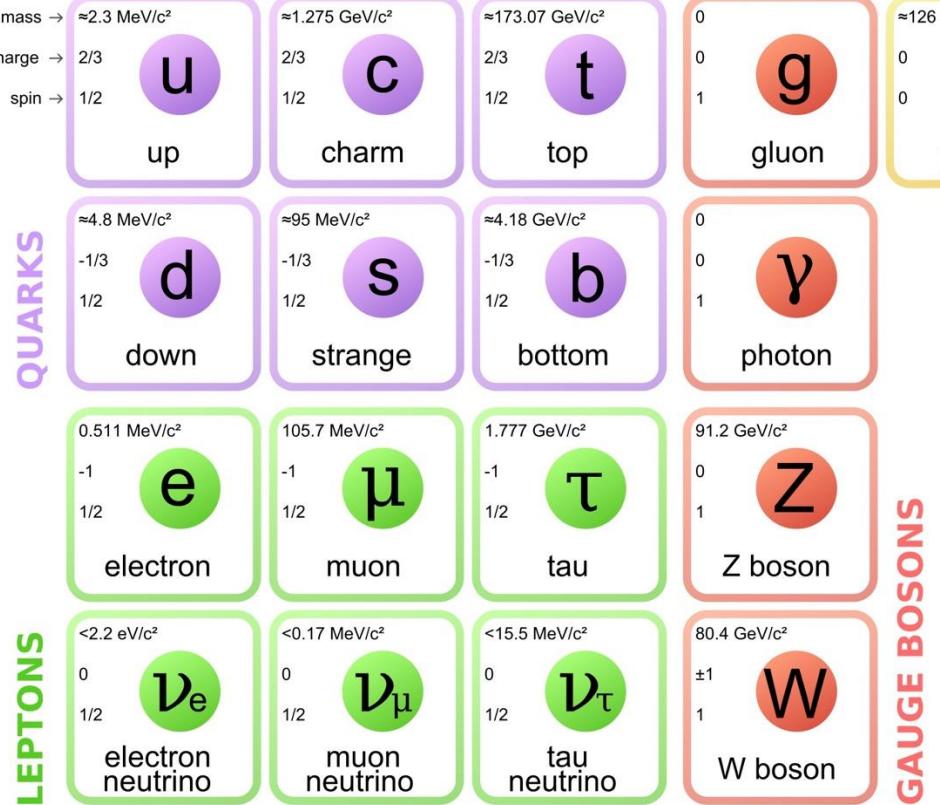
The Standard Model

QUARKS	mass →	$\approx 2.3 \text{ MeV}/c^2$	charge →	$2/3$	spin →	$1/2$	up
	charge →	$2/3$	spin →	$1/2$	mass →	$\approx 1.275 \text{ GeV}/c^2$	charm
LEPTONS	mass →	$\approx 173.07 \text{ GeV}/c^2$	charge →	$2/3$	spin →	$1/2$	top
	mass →	$\approx 4.18 \text{ GeV}/c^2$	charge →	$-1/3$	spin →	$1/2$	down
GAUGE BOSONS	mass →	$\approx 4.8 \text{ MeV}/c^2$	charge →	$-1/3$	spin →	$1/2$	strange
	mass →	$\approx 95 \text{ MeV}/c^2$	charge →	$-1/3$	spin →	$1/2$	bottom
GAUGE BOSONS	mass →	$0.511 \text{ MeV}/c^2$	charge →	-1	spin →	$1/2$ <th>electron</th>	electron
	mass →	$105.7 \text{ MeV}/c^2$	charge →	-1	spin →	$1/2$ <th>muon</th>	muon
GAUGE BOSONS	mass →	$1.777 \text{ GeV}/c^2$	charge →	-1	spin →	$1/2$ <th>tau</th>	tau
	mass →	$91.2 \text{ GeV}/c^2$	charge →	0	spin →	1	Z boson
GAUGE BOSONS	mass →	$<2.2 \text{ eV}/c^2$	charge →	0	spin →	$1/2$ <th>electron neutrino</th>	electron neutrino
	mass →	$<0.17 \text{ MeV}/c^2$	charge →	0	spin →	$1/2$ <th>muon neutrino</th>	muon neutrino
GAUGE BOSONS	mass →	$<15.5 \text{ MeV}/c^2$	charge →	0	spin →	$1/2$ <th>tau neutrino</th>	tau neutrino
	mass →	$80.4 \text{ GeV}/c^2$	charge →	± 1	spin →	1	W boson

Is Standard Model the
Final Theory?

(image credit: quantum diaries)

The Standard Model

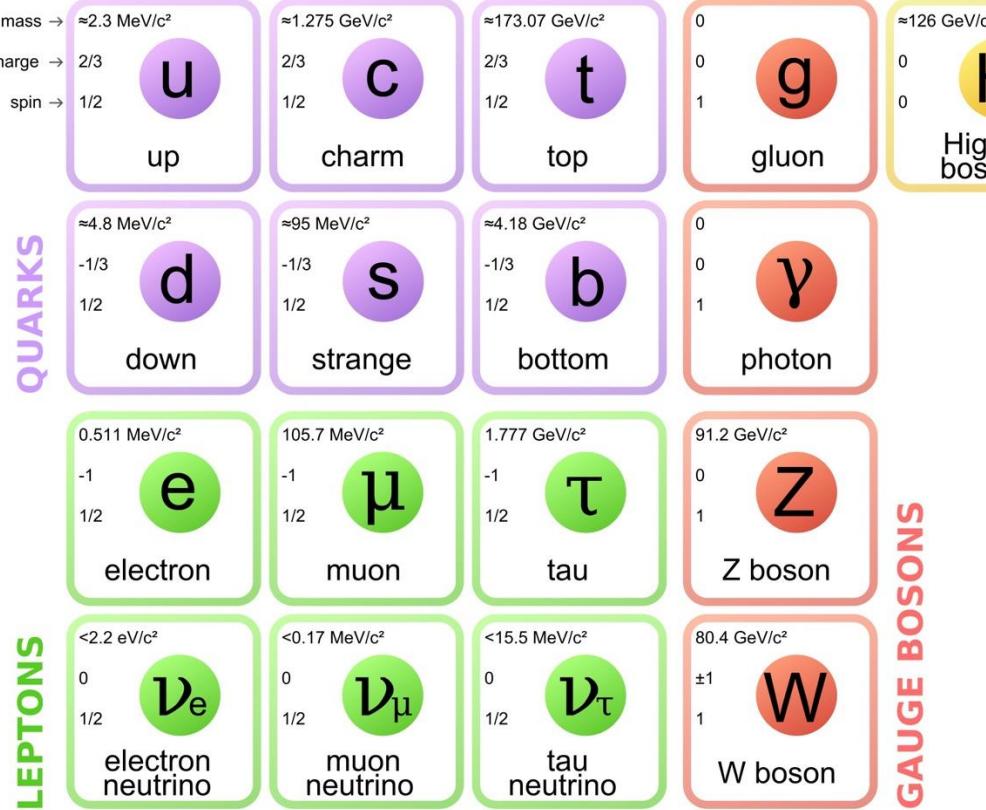


Is Standard Model the
Final Theory?

• Certainly not!

(image credit: quantum diaries)

The Standard Model



Is Standard Model the Final Theory?

• Certainly not!

- Dark Matter
- Neutrino Masses
- Matter-Antimatter Asymmetry
-

(image credit: quantum diaries)

The Model Symmetries

- The SM Symmetries:
- $SU(3)_C \times SU(2)_L \times U(1)_Y$

	mass →	$\approx 2.3 \text{ MeV}/c^2$	charge →	$2/3$	spin →	$1/2$	u	c	t	g	H
QUARKS	up	charm	top	gluon	Higgs boson						
mass →	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	0	0	d	s	b	γ	
charge →	$-1/3$	$-1/3$	$-1/3$	0	0	0	down	strange	bottom	photon	
spin →	$1/2$	$1/2$	$1/2$	1	1	1					
	mass →	$0.511 \text{ MeV}/c^2$	charge →	-1	spin →	$1/2$	e	μ	τ	Z	Gauge Bosons
LEPTONS	electron	muon	tau	Z boson							
mass →	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$			ν_e	ν_μ	ν_τ	W boson	
charge →	0	0	0	± 1			electron neutrino	muon neutrino	tau neutrino		
spin →	$1/2$	$1/2$	$1/2$	1							

The Model Symmetries

- Extra Symmetry:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

		mass \rightarrow	$\approx 2.3 \text{ MeV}/c^2$	charge \rightarrow	$2/3$	spin \rightarrow	$1/2$	mass \rightarrow	$\approx 1.275 \text{ GeV}/c^2$	charge \rightarrow	$2/3$	spin \rightarrow	$1/2$	mass \rightarrow	$\approx 173.07 \text{ GeV}/c^2$	charge \rightarrow	$2/3$	spin \rightarrow	$1/2$	mass \rightarrow	0	charge \rightarrow	0	spin \rightarrow	1	mass \rightarrow	$\approx 126 \text{ GeV}/c^2$	charge \rightarrow	0	spin \rightarrow	0			
		up	u	up				charm	c	charm				top	t	top				gluon	g	gluon				Higgs boson	H	Higgs boson						
		down	d	down				strange	s	strange				bottom	b	bottom				photon	γ	photon												
		electron	e	electron				muon	μ	muon				tau	τ	tau				Z boson	Z	Z boson												
		electron neutrino	ν_e	electron neutrino				muon neutrino	ν_μ	muon neutrino				tau neutrino	ν_τ	tau neutrino				W boson	W	W boson												
		LEPTONS		GAUGE BOSONS																														

The Model Symmetries

- Extra Symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

- What are the consequences of the new symmetry?

		mass \rightarrow	$\approx 2.3 \text{ MeV}/c^2$	charge \rightarrow	$2/3$	spin \rightarrow	$1/2$	name	symbol	mass \rightarrow	charge \rightarrow	spin \rightarrow	name	symbol	mass \rightarrow	charge \rightarrow	spin \rightarrow	name	symbol	mass \rightarrow	charge \rightarrow	spin \rightarrow	name	symbol	mass \rightarrow	charge \rightarrow	spin \rightarrow	name	symbol
QUARKS		up	u	charm	c	top	t	gluon	g	bottom	b	photon	γ	Higgs boson	H														
LEPTONS		down	d	strange	s	tau	τ	Z boson	Z	electron	e	muon	μ	tau neutrino	ν_τ	W boson	W	electron neutrino	ν_e	muon neutrino	ν_μ	tau neutrino	ν_τ	W	W				
GAUGE BOSONS		0.511 MeV/c ²	-1	105.7 MeV/c ²	-1	1.777 GeV/c ²	-1	91.2 GeV/c ²	0	<2.2 eV/c ²	0	<0.17 MeV/c ²	0	<15.5 MeV/c ²	0	80.4 GeV/c ²	± 1	0.511 MeV/c ²	-1	105.7 MeV/c ²	-1	1.777 GeV/c ²	-1	91.2 GeV/c ²	0	W	W		

The Model Symmetries

- Extra Symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

- What are the consequences of the new symmetry?

Z'

New gauge boson, Propagator of New force, Leptophilic

Φ

to produce the Z' mass

	mass \rightarrow	charge \rightarrow	spin \rightarrow	particle
up	$\approx 2.3 \text{ MeV}/c^2$	2/3	1/2	u
charm	$\approx 1.275 \text{ GeV}/c^2$	2/3	1/2	c
top	$\approx 173.07 \text{ GeV}/c^2$	2/3	1/2	t
gluon	0	0	1	g
Higgs boson	$\approx 126 \text{ GeV}/c^2$	0	0	H
QUARKS				
down	$\approx 4.8 \text{ MeV}/c^2$	-1/3	1/2	d
strange	$\approx 95 \text{ MeV}/c^2$	-1/3	1/2	s
bottom	$\approx 4.18 \text{ GeV}/c^2$	-1/3	1/2	b
photon	0	0	1	γ
LEPTONS				
electron	$0.511 \text{ MeV}/c^2$	-1	1/2	e
muon	$105.7 \text{ MeV}/c^2$	-1	1/2	μ
tau	$1.777 \text{ GeV}/c^2$	-1	1/2	τ
Z boson	$91.2 \text{ GeV}/c^2$	0	1	Z
W boson	$80.4 \text{ GeV}/c^2$	± 1	1	W
GAUGE BOSONS				

Why Studying this Model ?

- Simplest Extension  Searching New Particles at Colliders

[G.Huang, F.S.Queiroz, W.Rodejohann, arXiv:2101.04956]

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- Mediator to the Dark Sector

[W. Altmannshofer, S. Gori, S. Profumo, F. S. Queiroz, arXiv: 1609.04026]

Model B-L

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \boxed{U(1)_{B-L}}$$

Model B-L

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B - L$
q_L	3	2	$\frac{1}{6}$	$\frac{1}{3}$
u_R	3	1	$\frac{2}{3}$	$\frac{1}{3}$
d_R	3	1	$-\frac{1}{3}$	$\frac{1}{3}$
l_L	1	2	$-\frac{1}{2}$	-1
e_R	1	1	-1	-1
ν_R	1	1	0	-1

Fermion content and charges for the $B - L$ model.

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B - L$
H	1	2	$\frac{1}{2}$	0
χ	1	1	0	2

Scalar content and charges for the $B - L$ model.

[Basso, Belyaev, Moretti, Shepherd-Themistocleous(2008)]

$L_\mu - L_\tau$ Model

B-L model Variant:

$L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ Models

Gauge group	L_e	L_μ	L_τ	e_R	μ_R	τ_R	H	Φ
$SU(3)_c$	1	1	1	1	1	1	1	1
$SU(2)_L$	2	2	2	1	1	1	2	1
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	$\frac{1}{2}$	0
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	2

$L_\mu - L_\tau$ Model

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Gauge group	L_e	L_μ	L_τ	e_R	μ_R	τ_R	H	Φ
$SU(3)_c$	1	1	1	1	1	1	1	1
$SU(2)_L$	2	2	2	1	1	1	2	1
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	$\frac{1}{2}$	0
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	2

$$\mathcal{L}_{\mu-\tau} = g' Z'_\nu (\bar{L}_\mu \gamma^\nu L_\mu - \bar{L}_\tau \gamma^\nu L_\tau + \bar{\mu}_R \gamma^\nu \mu_R - \bar{\tau}_R \gamma^\nu \tau_R) + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu$$

New coupling

$$M_{Z'} = 2g' v_\Phi$$

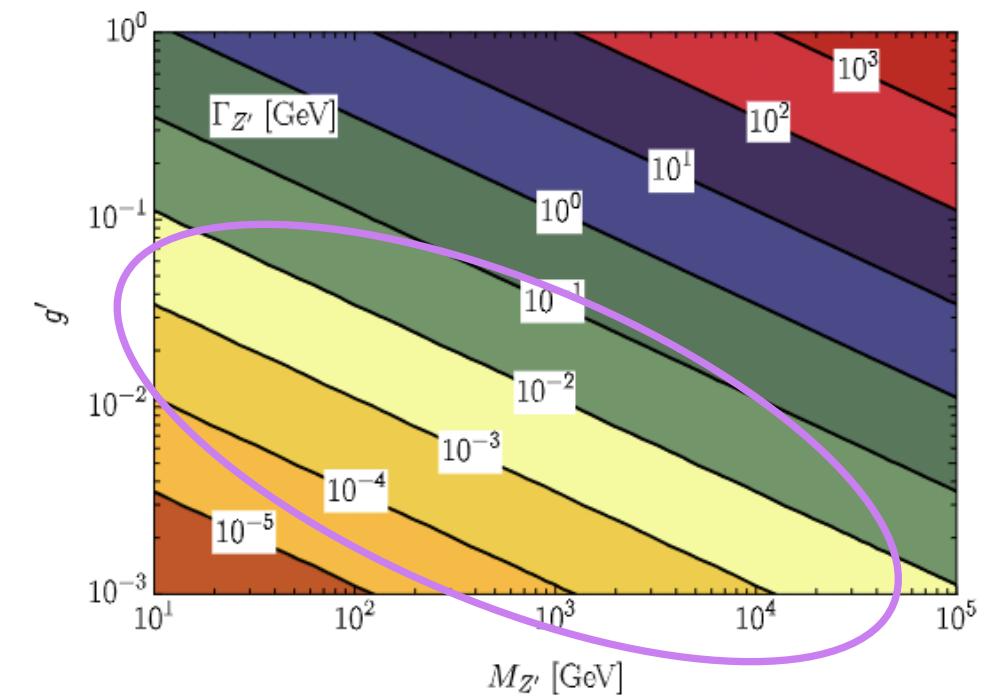
Z' Particle

$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi}$$

Ignore lepton masses

$$\Gamma(Z' \rightarrow l\bar{l}) = 2\Gamma(Z' \rightarrow \nu\bar{\nu})$$

$$\boxed{\Gamma_{tot} = \frac{(2N_l + N_\nu)g'^2}{24\pi} M_{Z'} = \frac{6g'^2}{24\pi} M_{Z'}}$$



Z' Particle

No RH LH difference

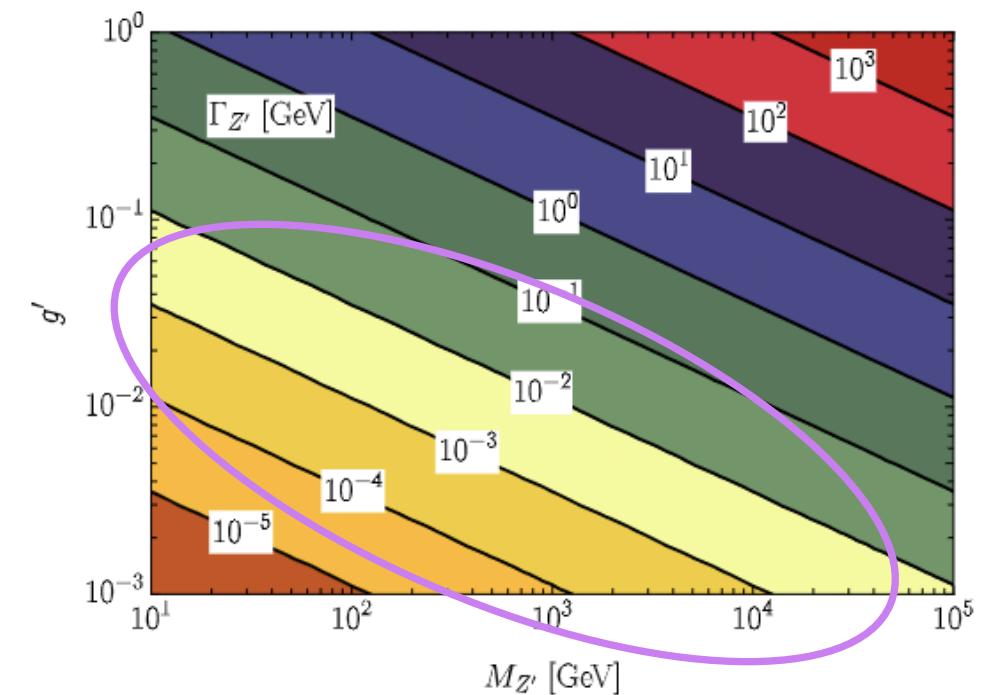
$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi} \quad \text{Ignore lepton masses}$$

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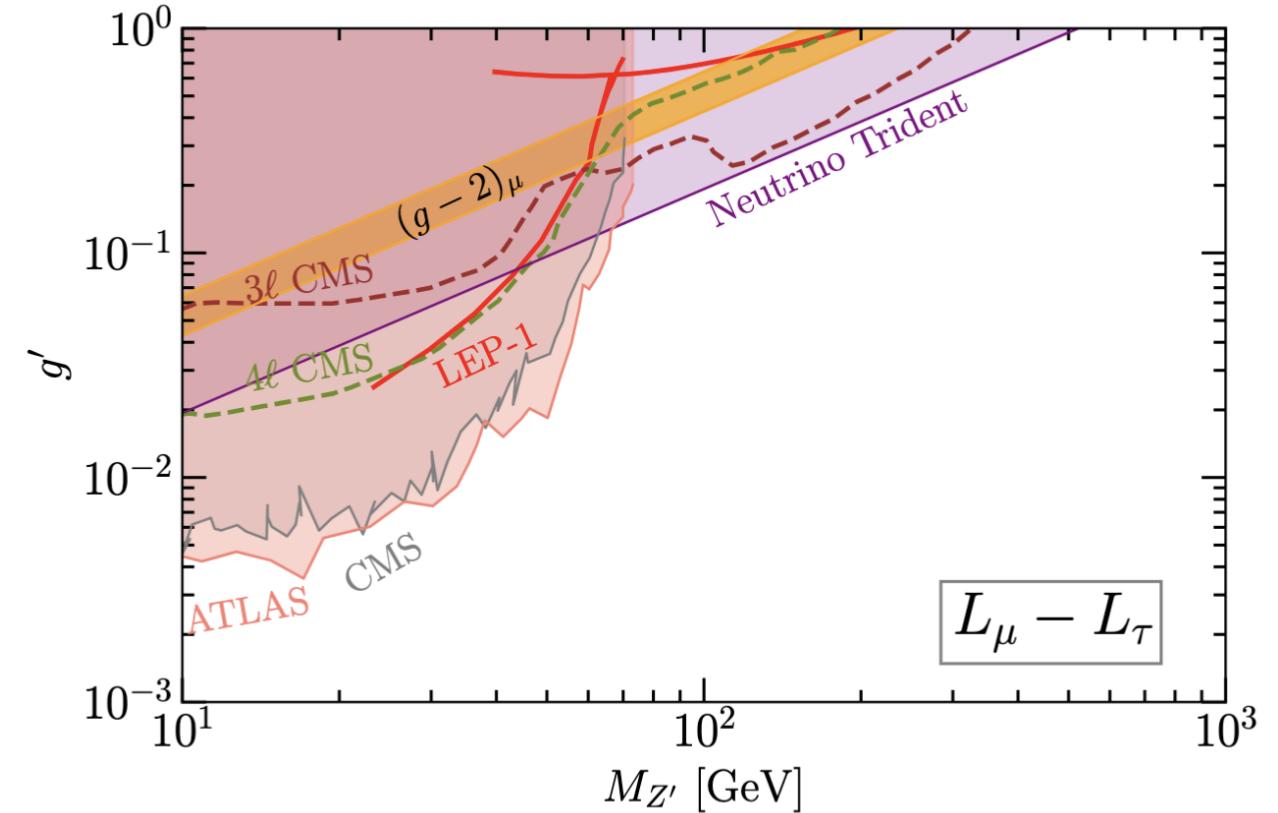
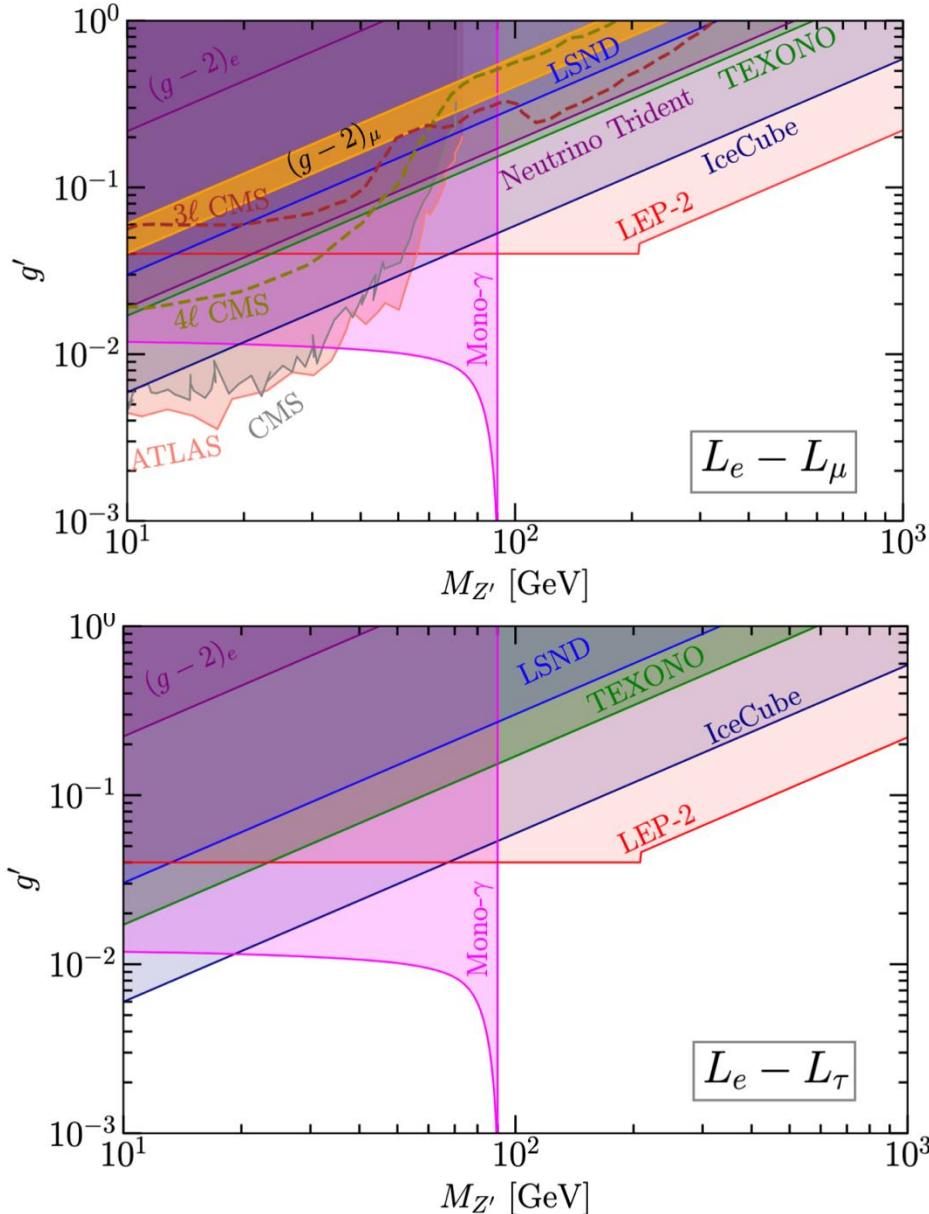
Proper decay length:

$$c\tau = \frac{c}{\Gamma(Z')} = 2.48 \times 10^{-4} \mu m \left(\frac{10^{-3}}{g'} \right)^2 \left(\frac{10 \text{ GeV}}{M_{Z'}} \right) \quad \text{Prompt decay}$$



Current Constraints

Current Exclusion Bounds



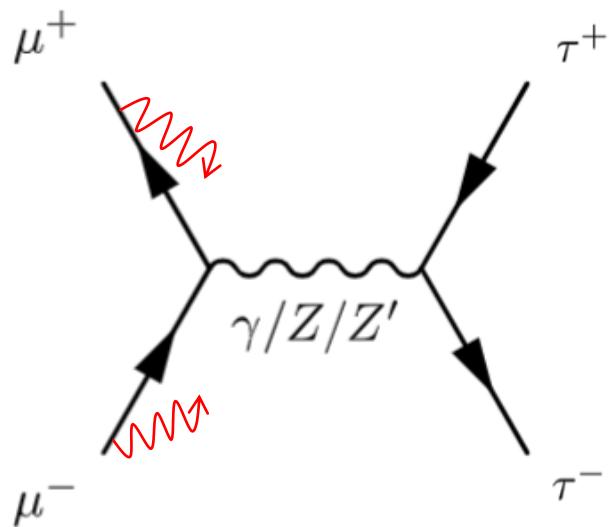
Current:

- LHC: ATLAS, CMS
- Neutrino scattering: LSND, TEXONO
- LEP, IceCube, $(g-2)_l$

Muon Collider Searching

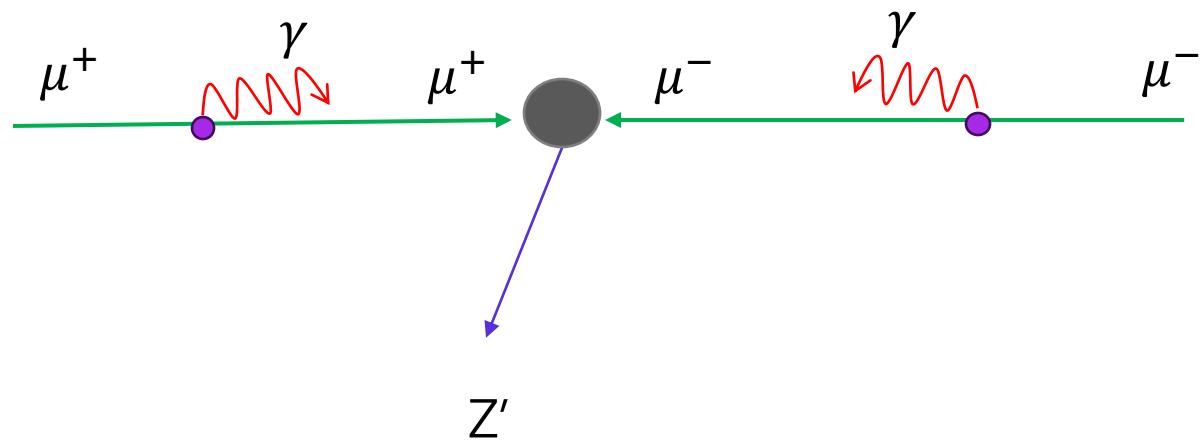
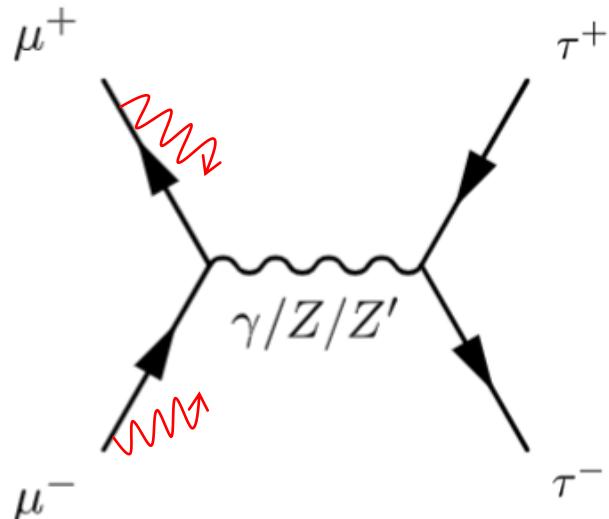
Z' Particle On-Shell (resonance) Production

$\mu^+ \mu^- \rightarrow \tau^+ \tau^-$ With Initial State Radiation (ISR)



Z' Particle On-Shell (resonance) Production

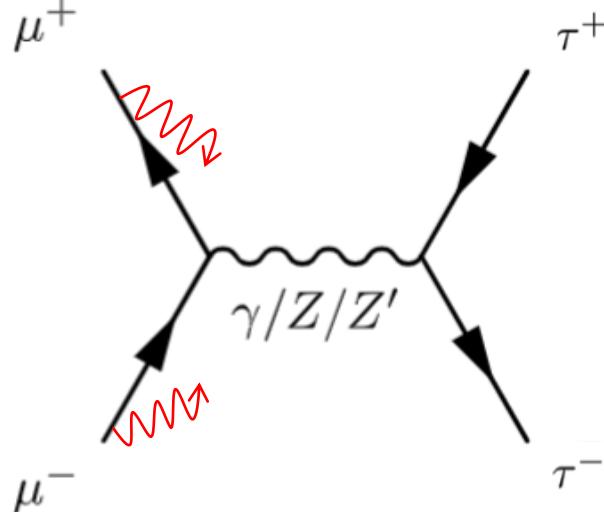
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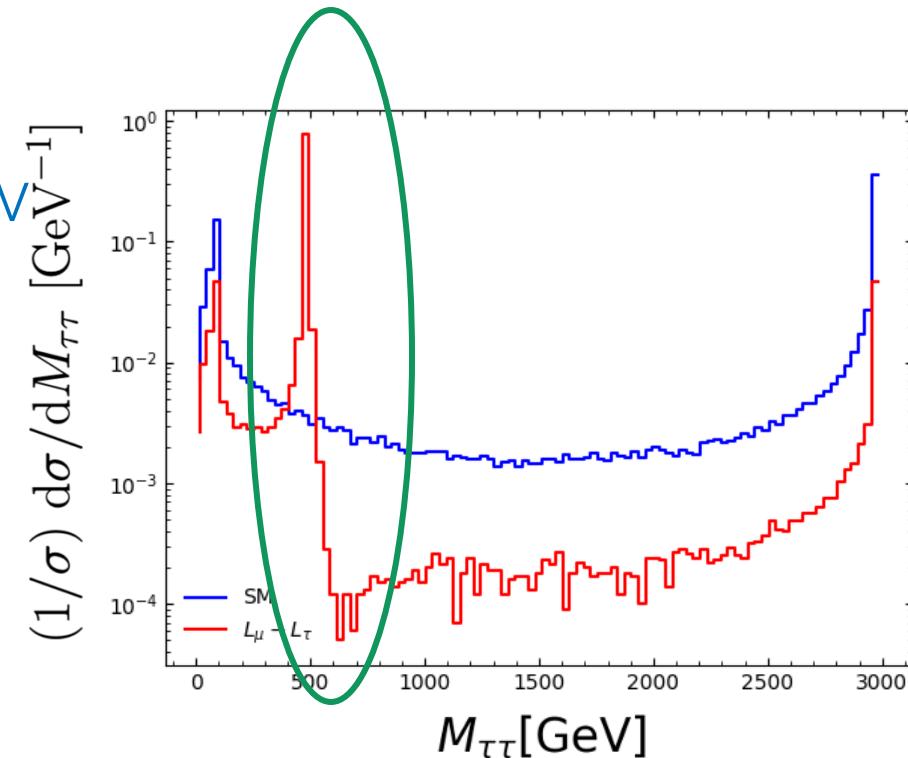
$$E^2 = p^2 + m^2$$

Z' Particle On-Shell (resonance) Production

$\mu^+ \mu^- \rightarrow \tau^+ \tau^-$ With Initial State Radiation (ISR)



$\sqrt{s} = 3 \text{ TeV}$
 $M_{Z'} = 500 \text{ GeV}$
 $g' = 0.2$



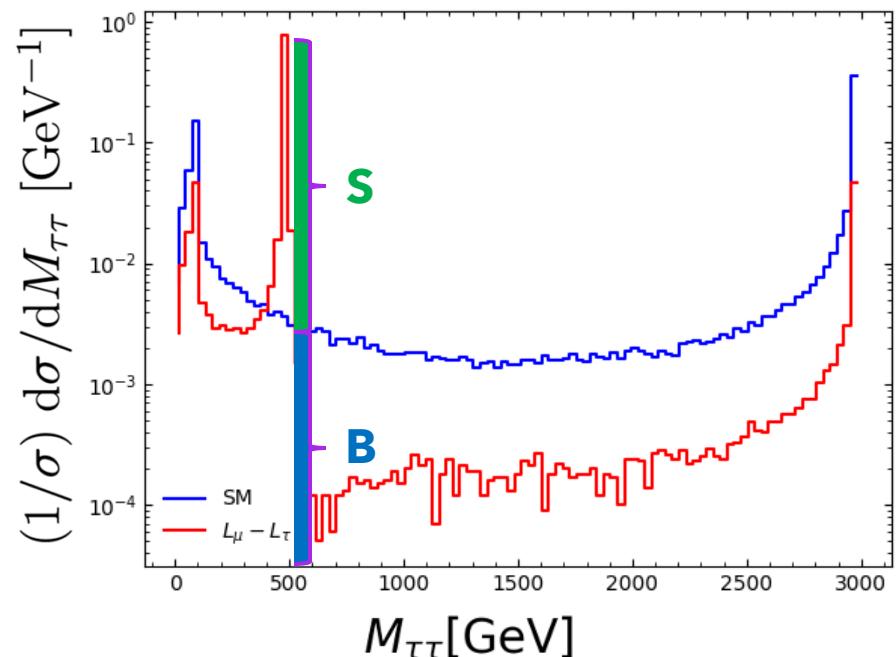
propagator:

$$\frac{1}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma^2} \xrightarrow{\text{peak}}$$

Z' Particle On-Shell (resonance) Production

Sensitivity

$\mu^+ \mu^- \rightarrow \tau^+ \tau^-$ With Initial State Radiation (ISR)



$$\sqrt{s} = 3 \text{ TeV}$$

$$M_{Z'} = 500 \text{ GeV}$$

$$g' = 0.2$$

For $M_{Z'}$, from 100 GeV to 3TeV

Significance:

$$\mathcal{S} = \frac{S}{\sqrt{S + B + \delta^2(S + B)^2}} = 2 \quad (\text{equivalent to 95% CL})$$

$$S = N^{SM+Z'} - N^{SM} = \epsilon \mathcal{L} (\sigma^{SM+Z'} - \sigma^{SM})$$

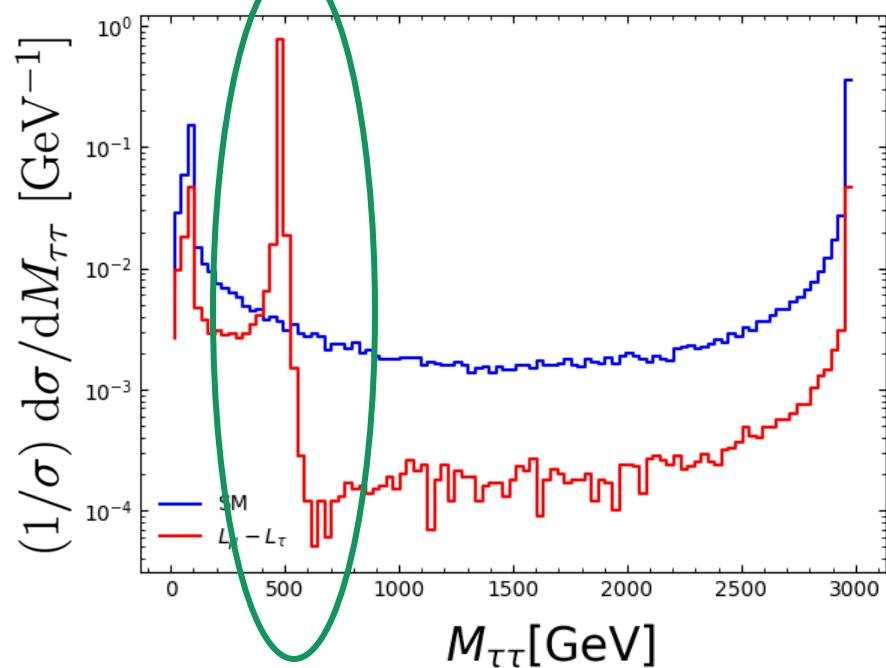
$$B = N^{SM} = \epsilon \mathcal{L} \sigma^{SM}$$

Whizard

Z' Particle On-Shell (resonance) Production

Selection Cuts

$\mu^+ \mu^- \rightarrow \tau^+ \tau^-$ With Initial State Radiation (ISR)



Pre-selection Cuts:

$$p_T^\ell > 30 \text{ GeV}, |\eta_\ell| < 2.44, \Delta R_{\ell\ell} > 0.3$$

$$\sqrt{s} = 3 \text{ TeV}$$

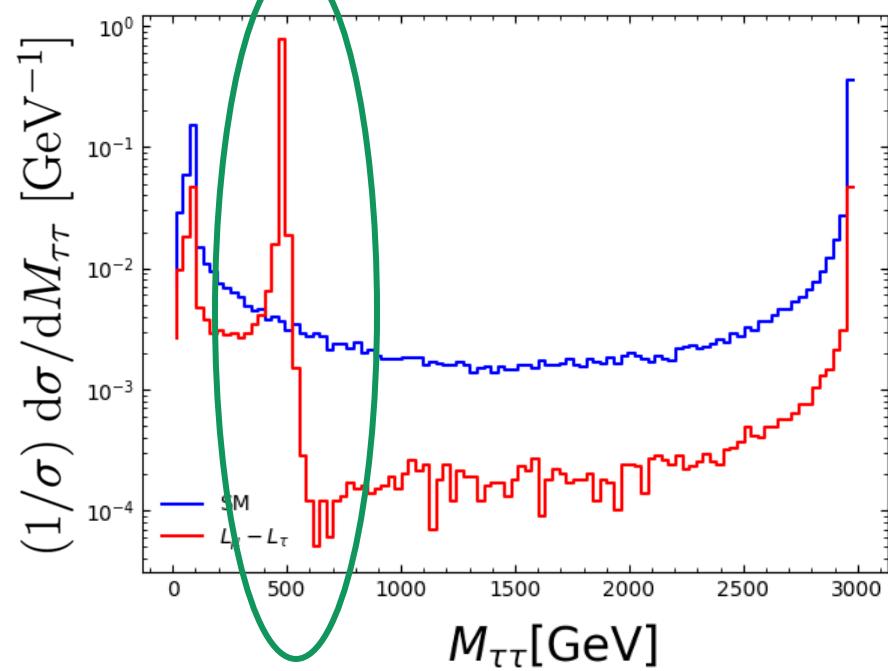
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Optimization Cuts:

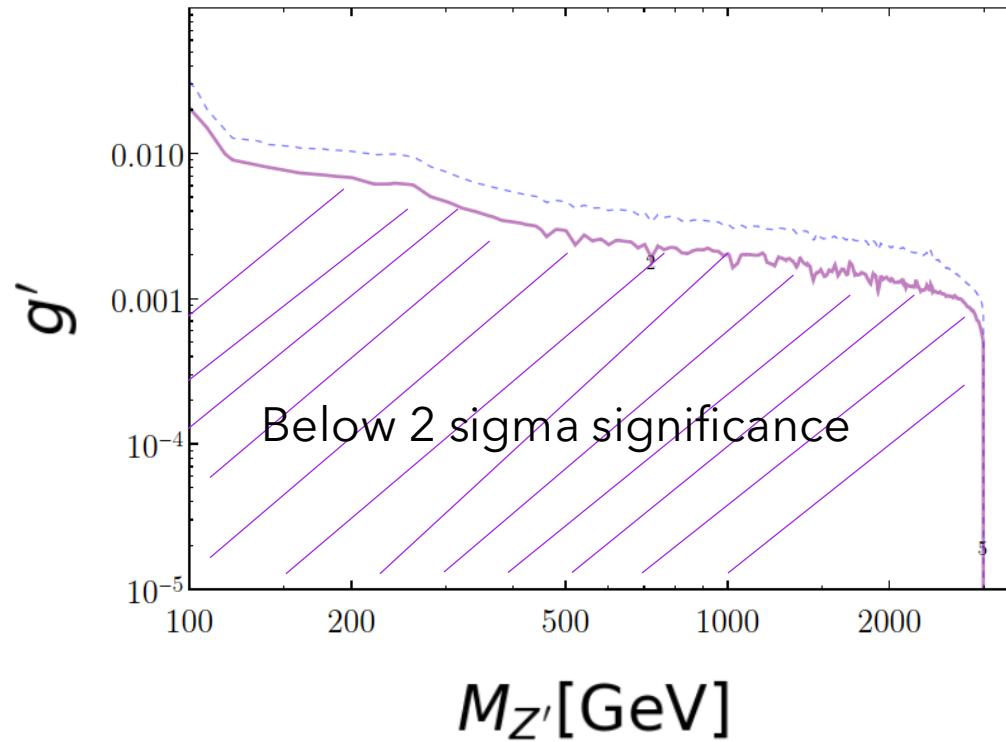
$$|M_{\ell\ell} - M_{Z'}| < 0.05M_{Z'}$$

\uparrow
 τ

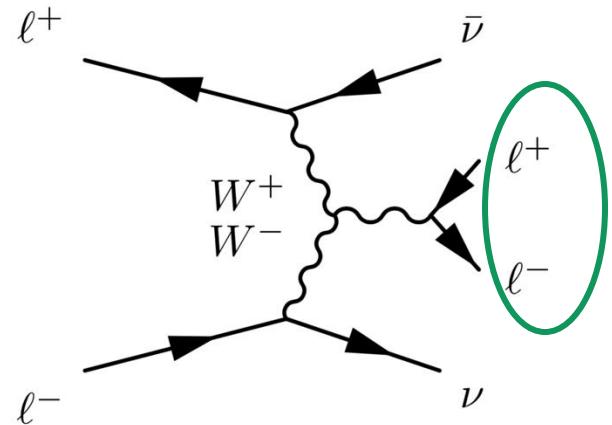
Z' Particle On-Shell (resonance) Production

$\mu^+ \mu^- \rightarrow \tau^+ \tau^-$ with ISR

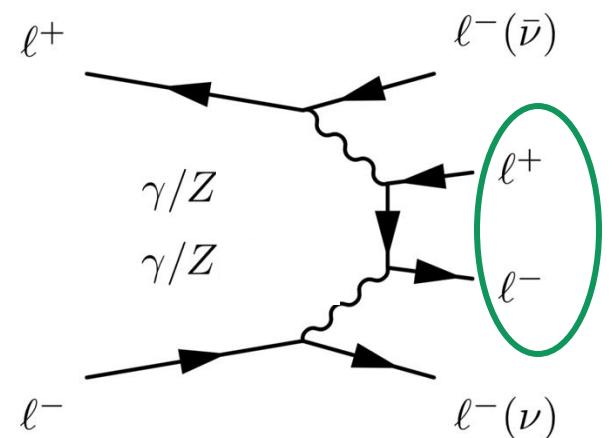
$\sqrt{s} = 3 \text{ TeV}$
 $\mathcal{L} = 1 \text{ ab}^{-1}$



Vector Boson Fusion (VBF) Background

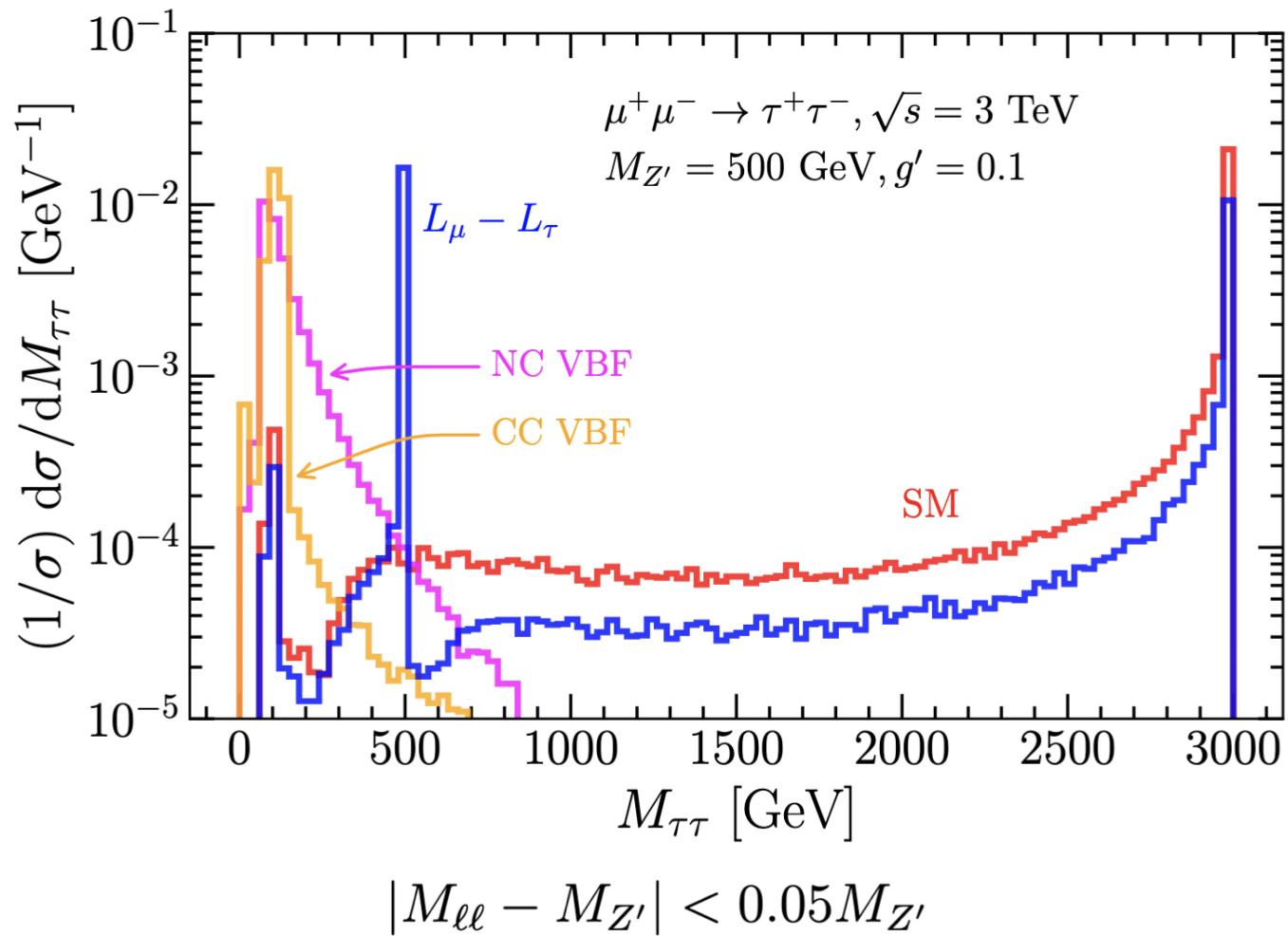
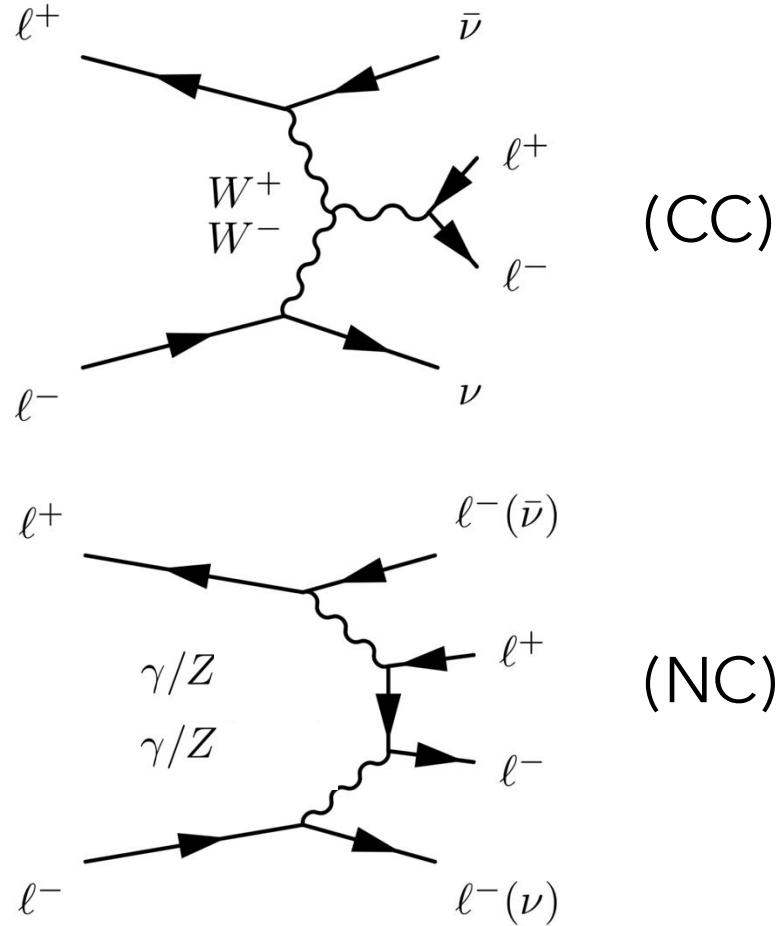


Charge Current (CC) VBF



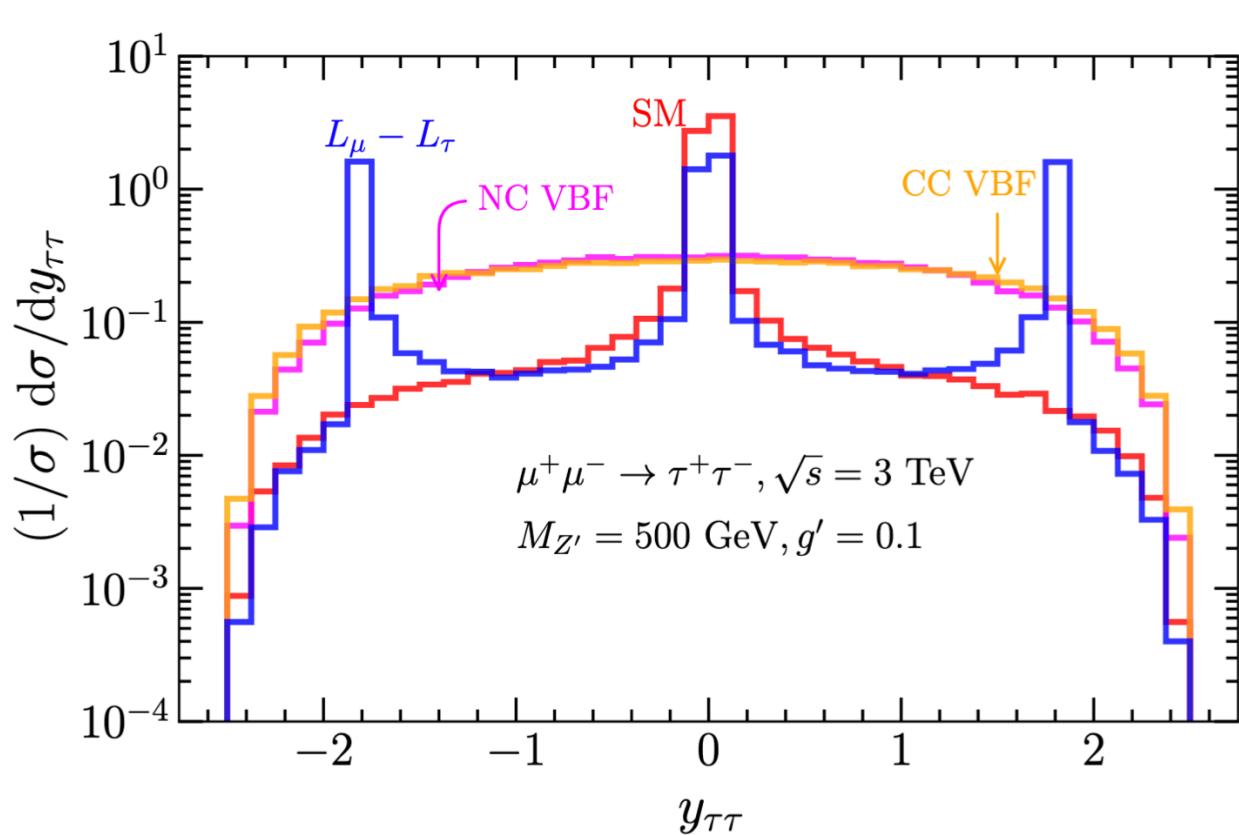
Neutral Current (NC) VBF

Vector Boson Fusion (VBF) Background



Z' Particle On-Shell (resonance) Production

System Rapidity Cut



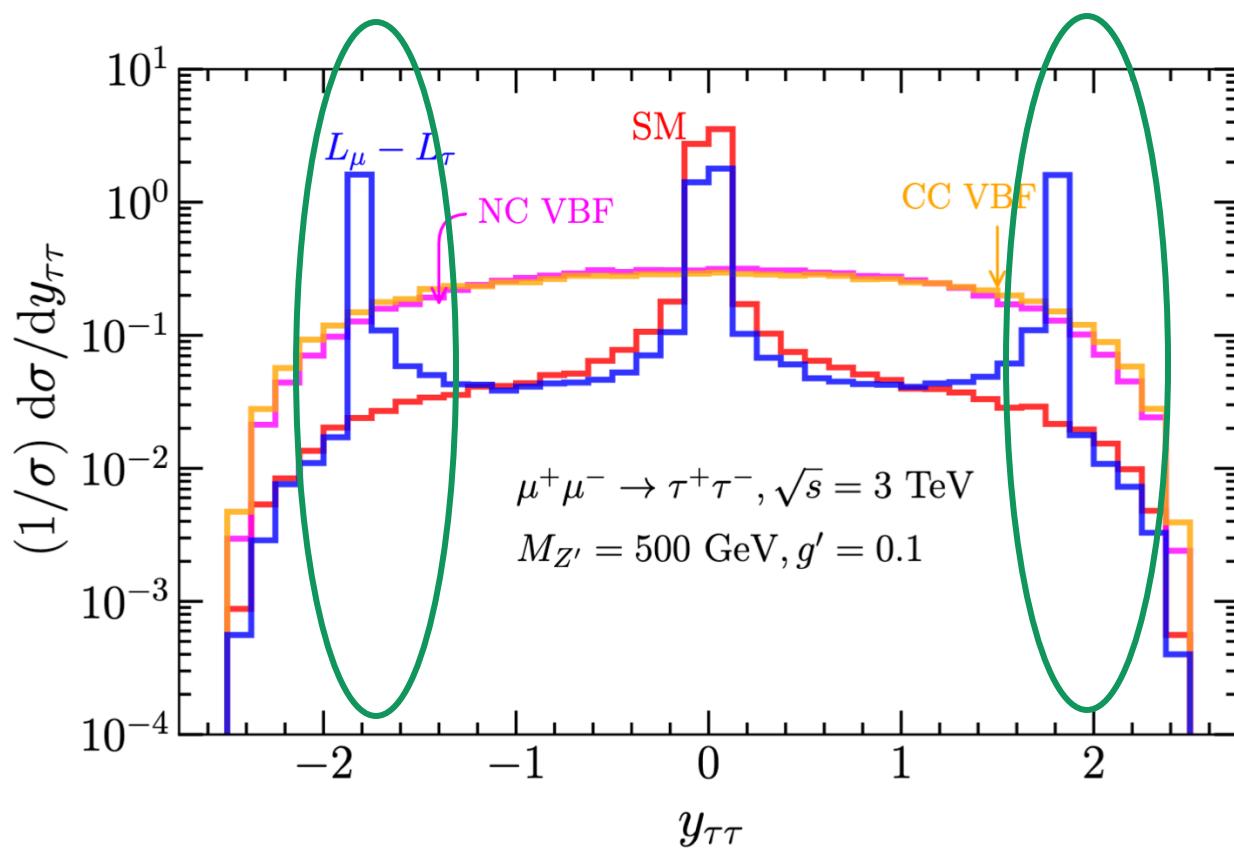
$$\eta = -\frac{1}{2} \ln \tan \frac{\theta}{2}$$

Additional Optimization Cuts:

$$|y_{\tau\tau} \pm y_{Z'}| < 0.2$$

Z' Particle On-Shell (resonance) Production

System Rapidity Cut



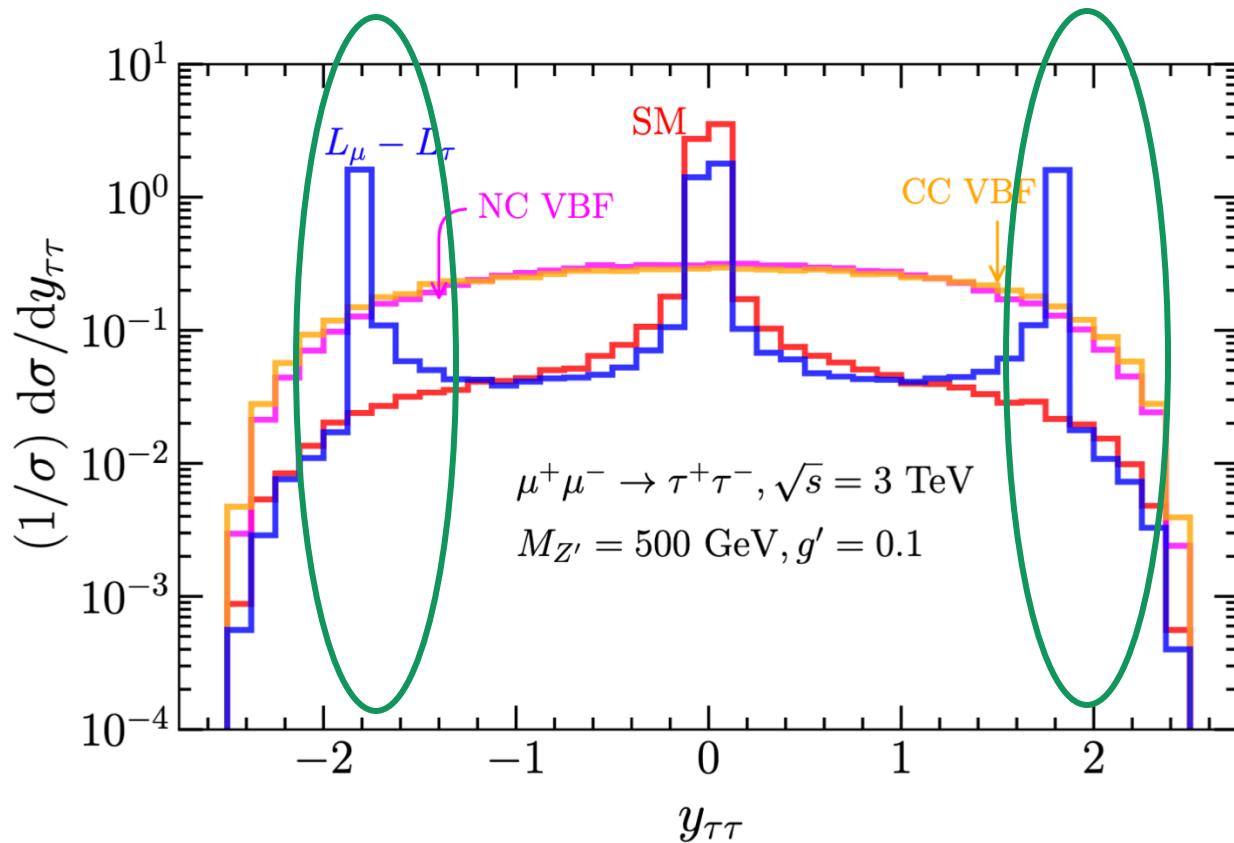
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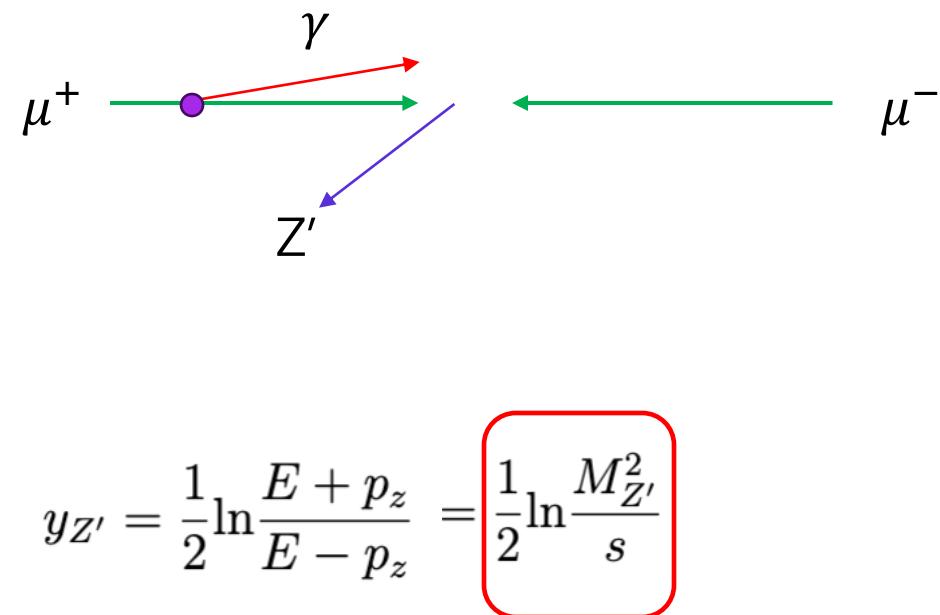
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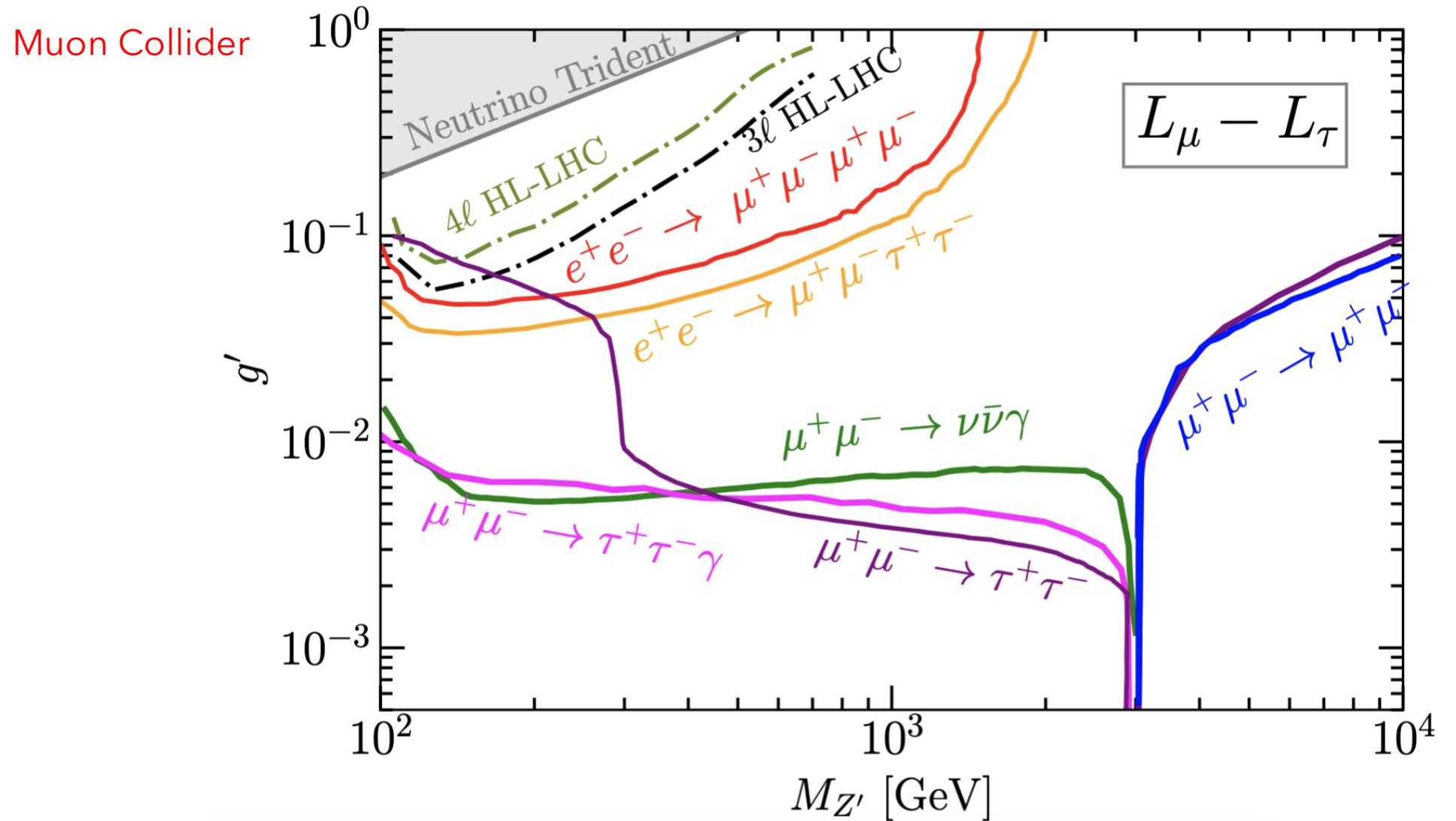
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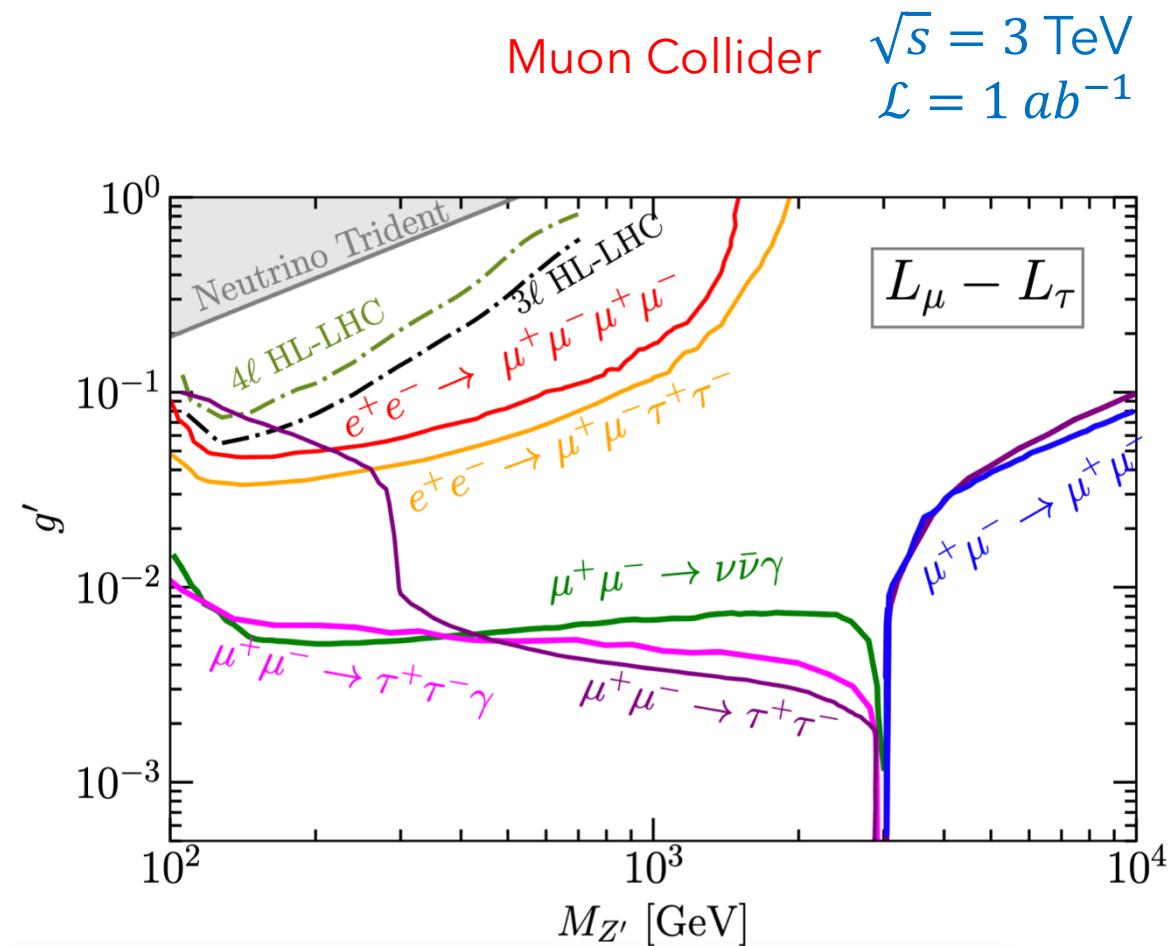
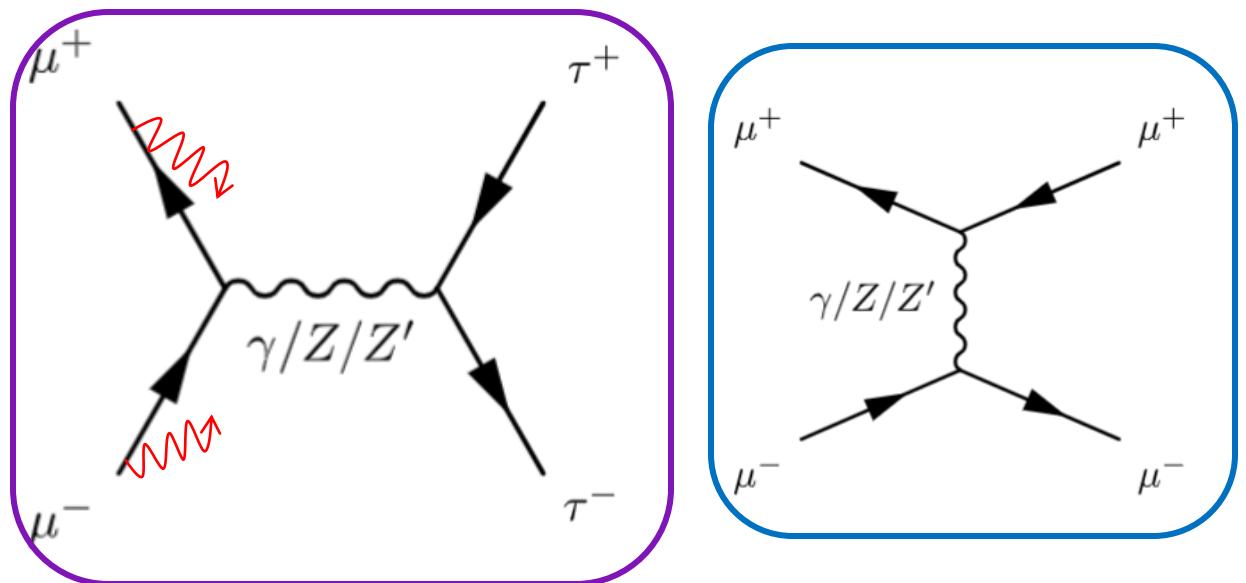
Final Significance Plots

Significance Plot

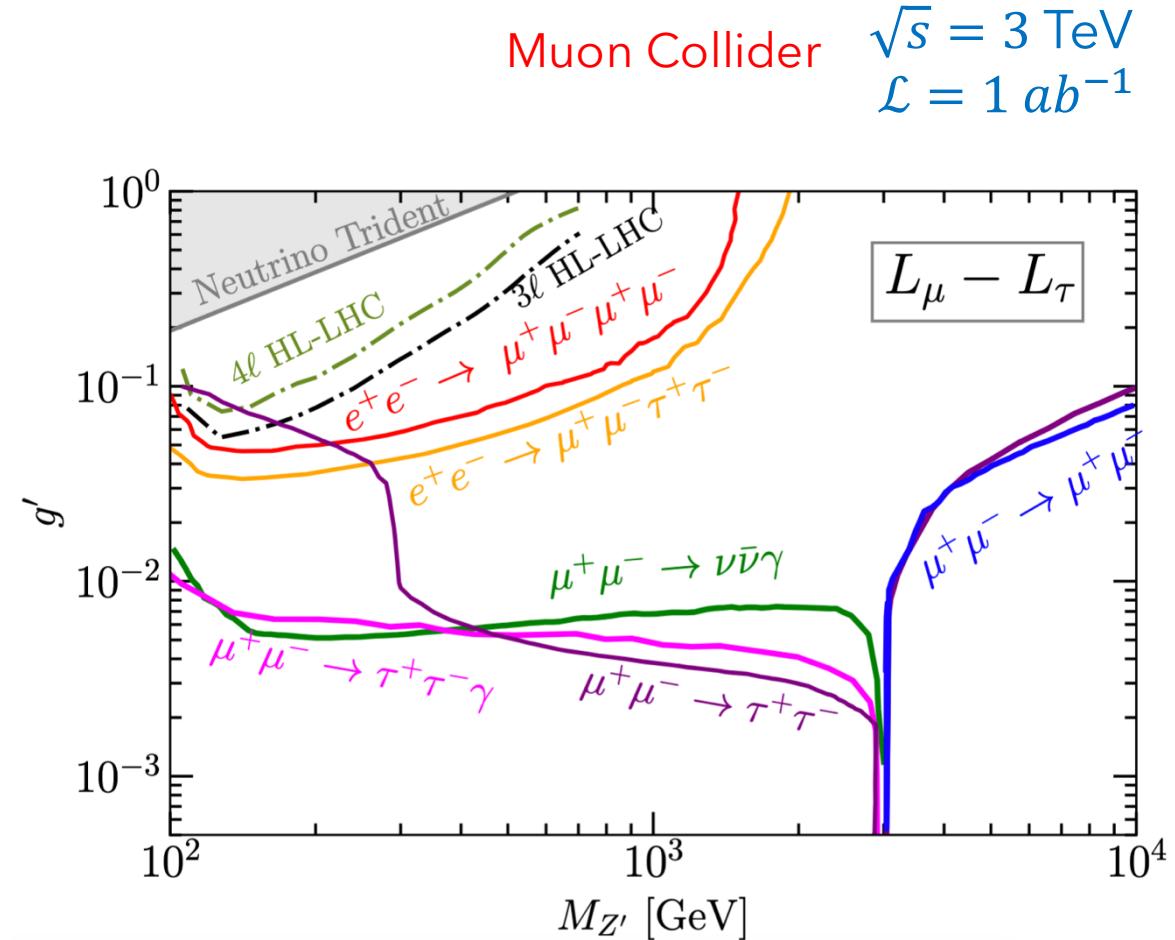
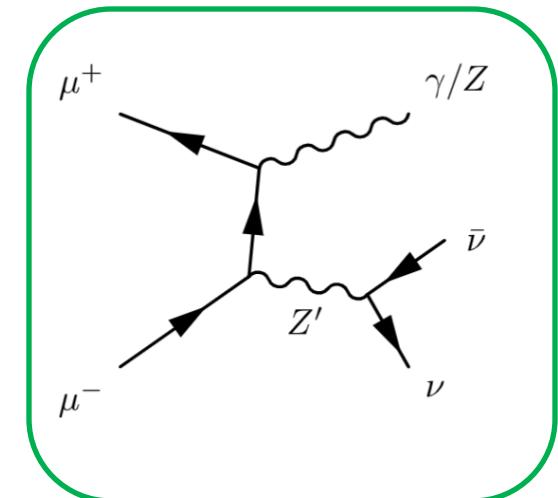
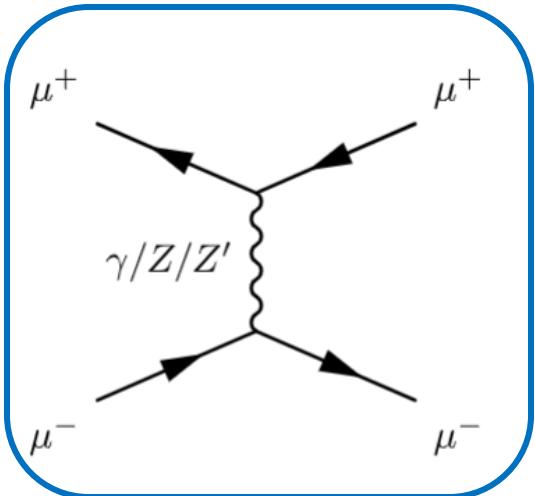
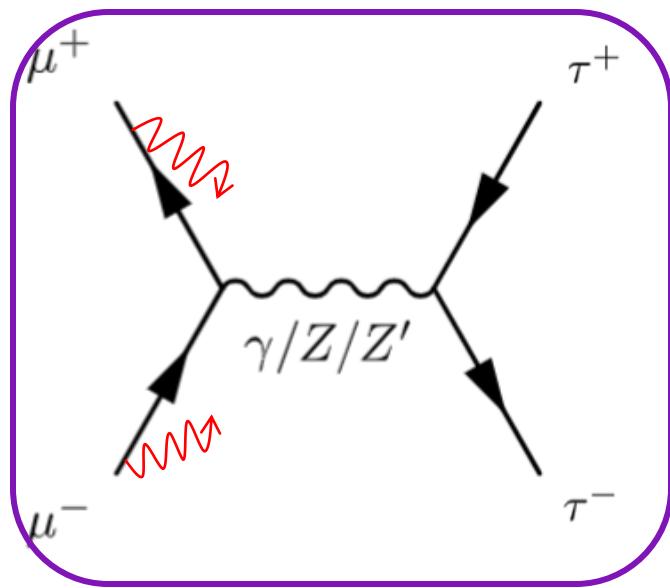


$\sqrt{s} = 3 \text{ TeV}$
 $\mathcal{L} = 1 \text{ ab}^{-1}$

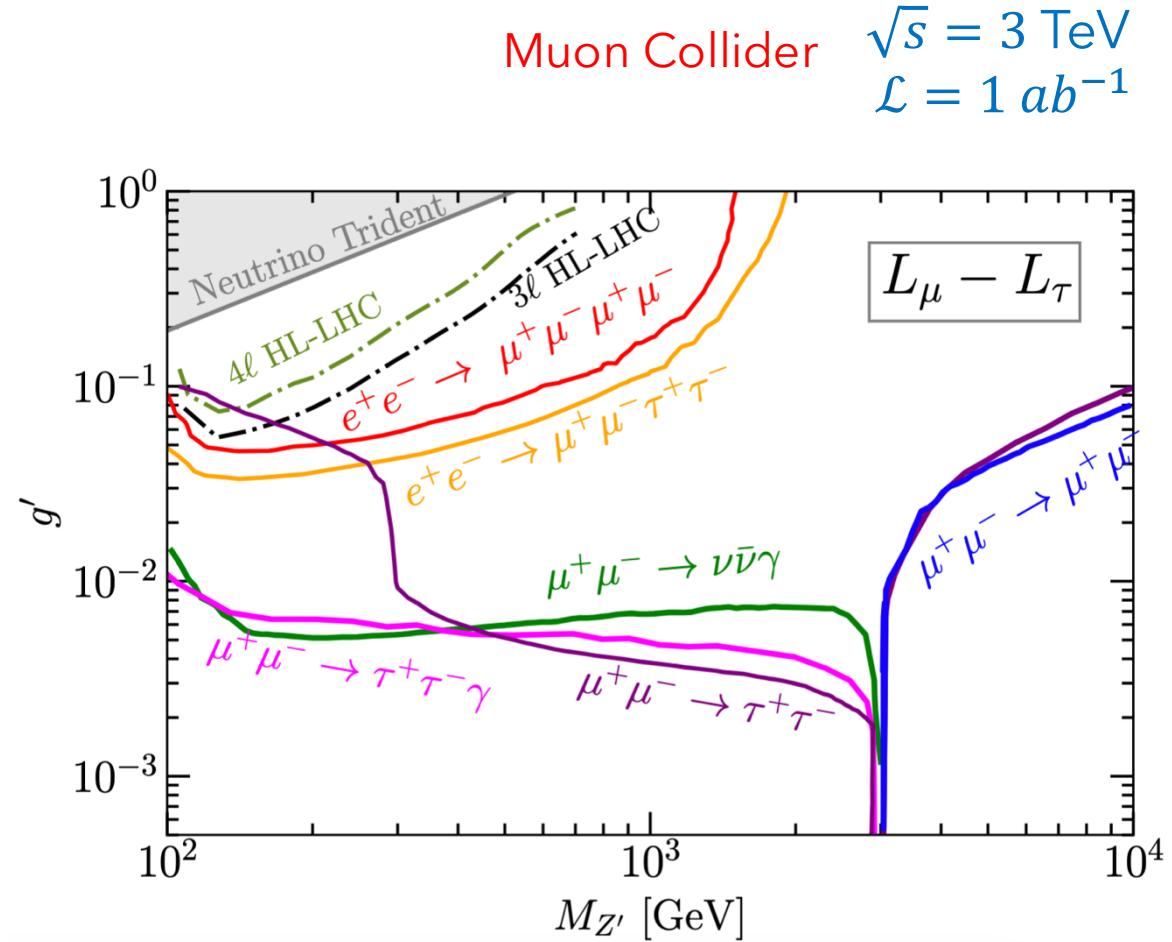
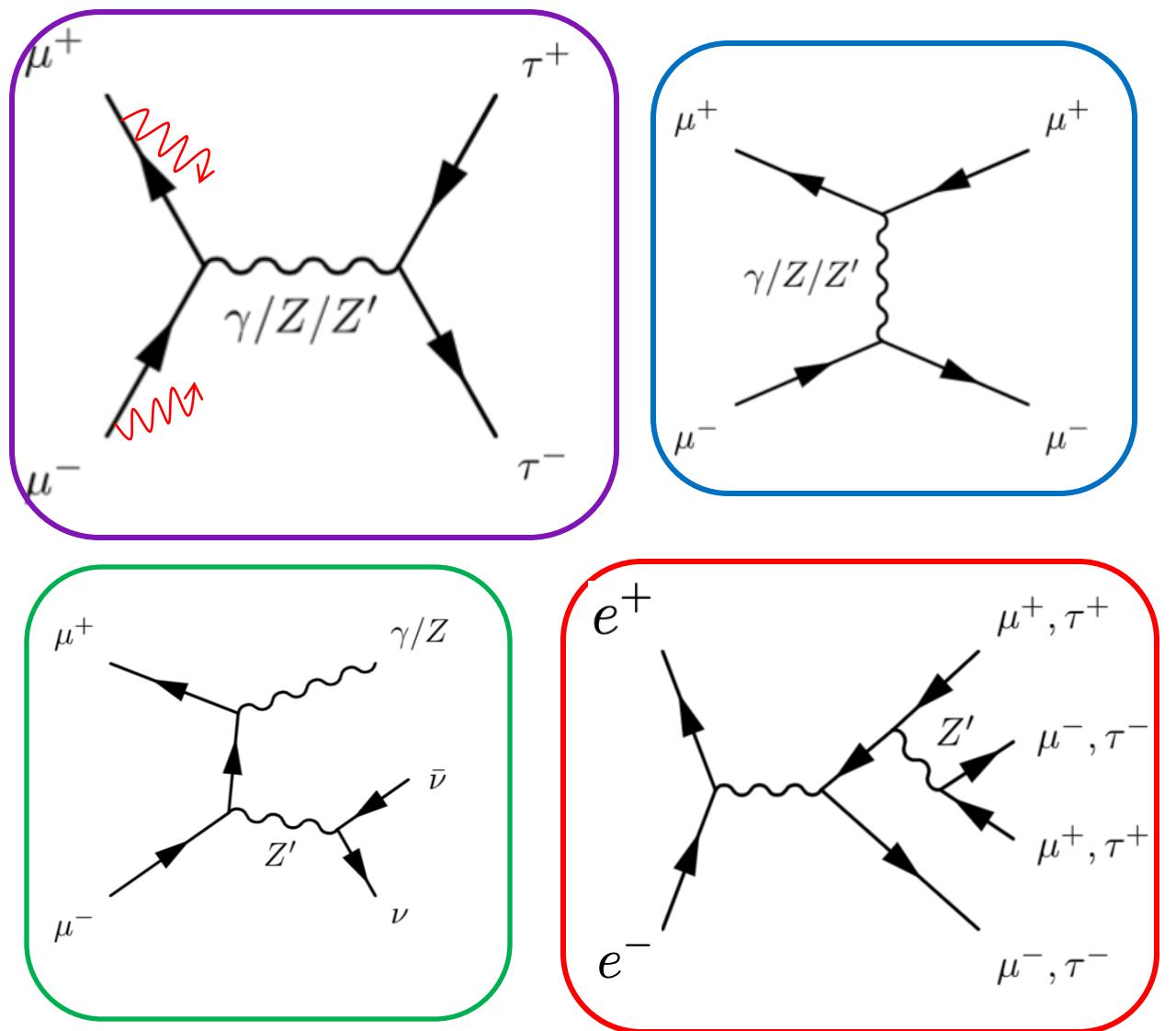
Significance Plot



Significance Plot

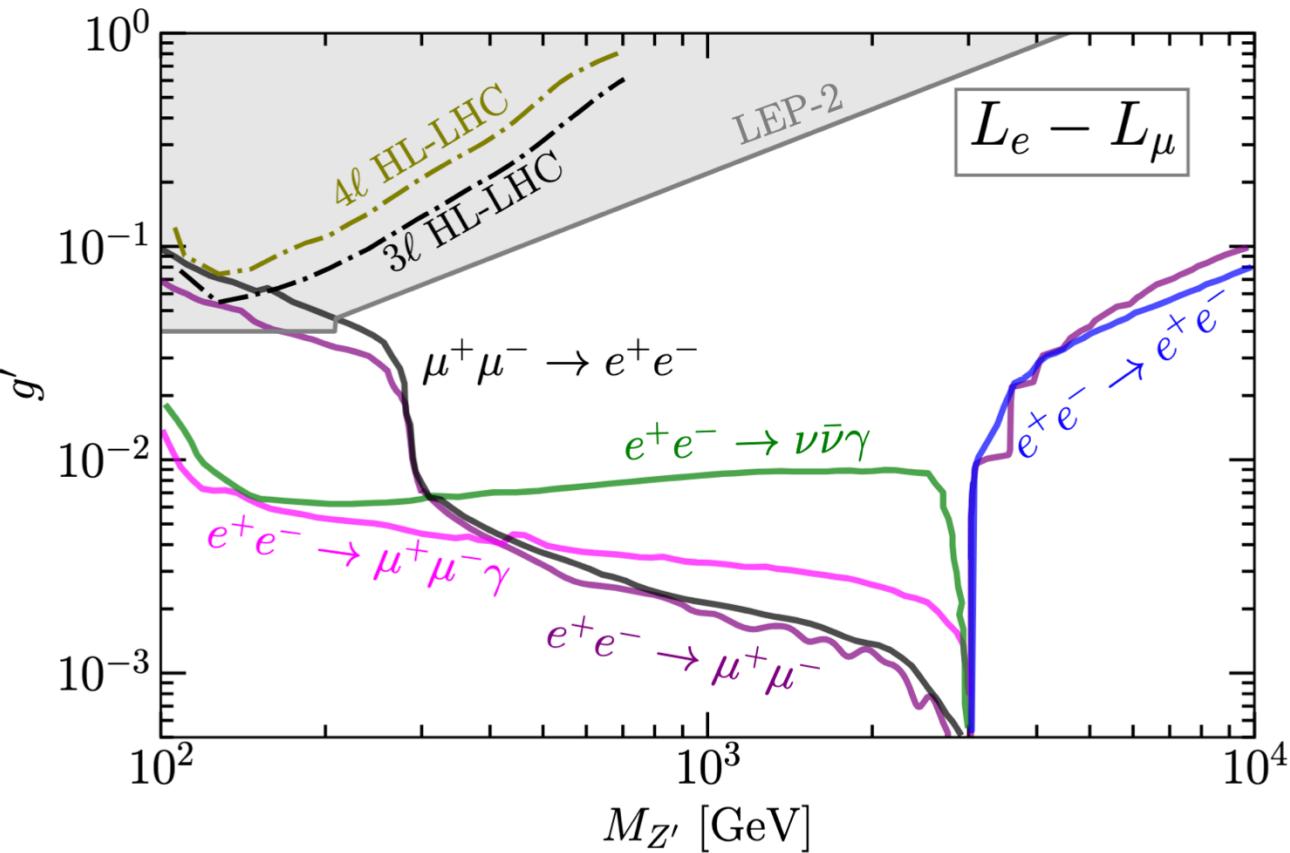


Significance Plot

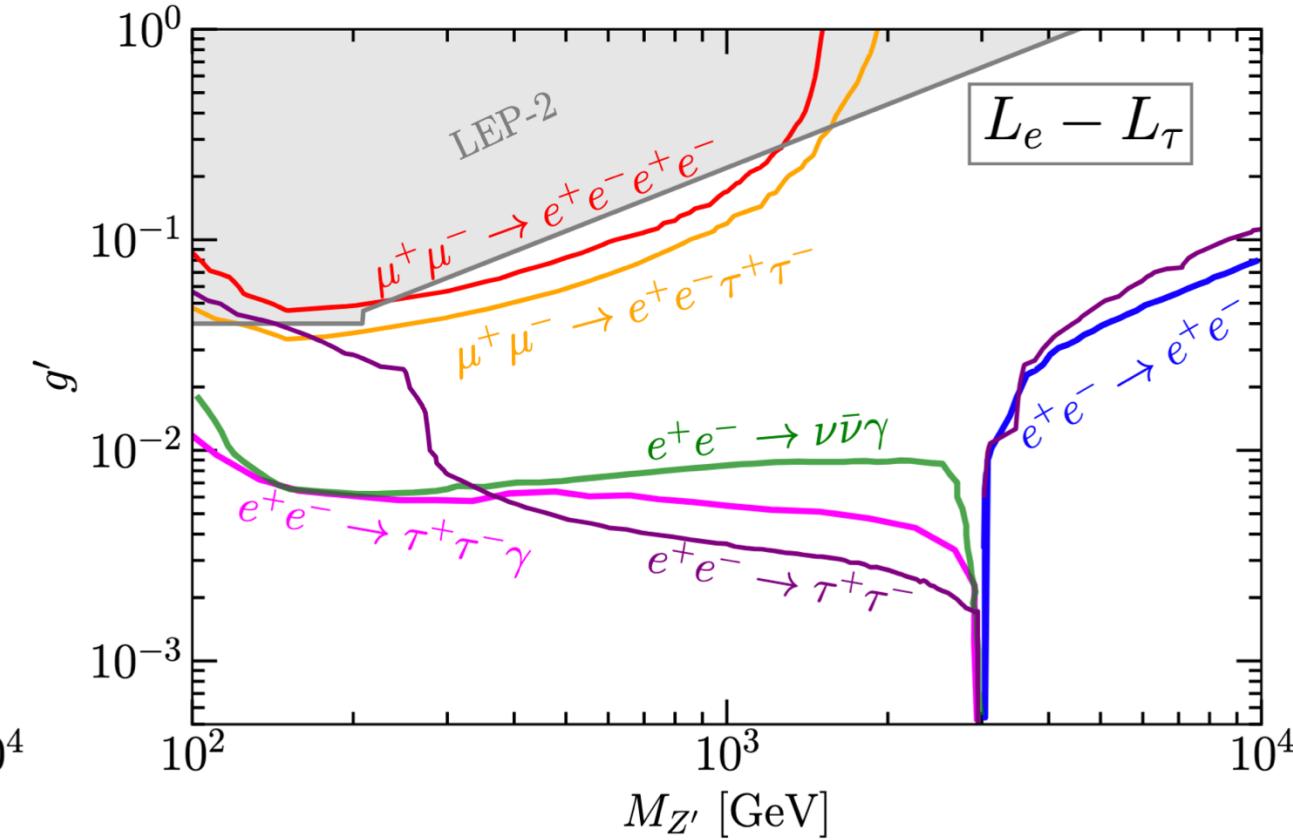


Significance Plots

Electron Collider



$\sqrt{s} = 3 \text{ TeV}$
 $\mathcal{L} = 1 \text{ ab}^{-1}$



Gravitationanl Waves Part

New Scalar Field Effective Potential



$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi)$$



$$\frac{1}{4}\lambda\phi^4$$

New Scalar Field Effective Potential



$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi)$$

$$\frac{1}{4}\lambda\phi^4$$

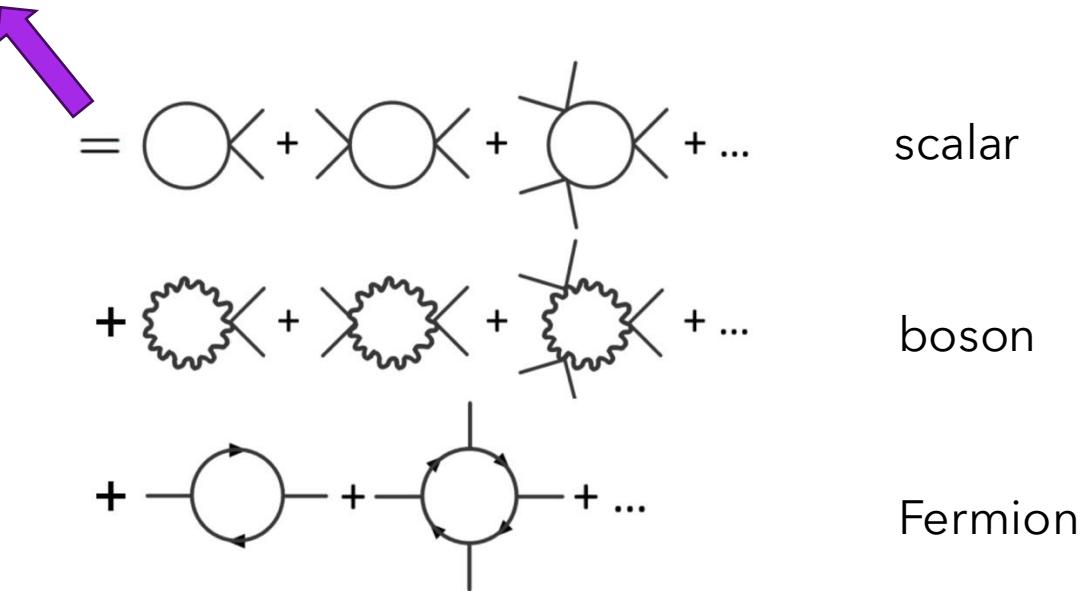


Image credit: Arthur Wu

New Scalar Field Effective Potential



$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi) + V_{\text{1-loop}}(\phi)$$

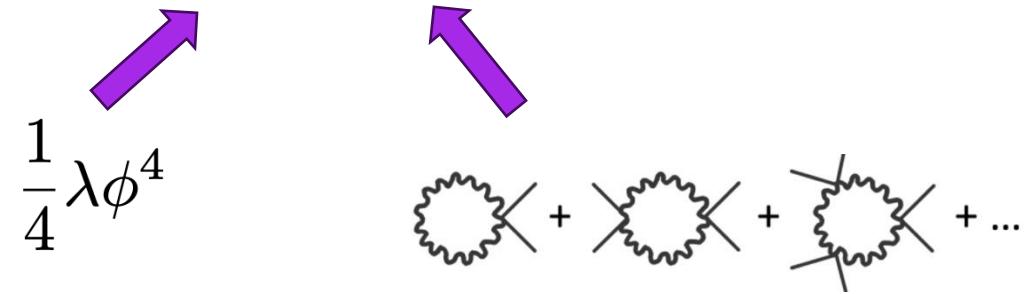


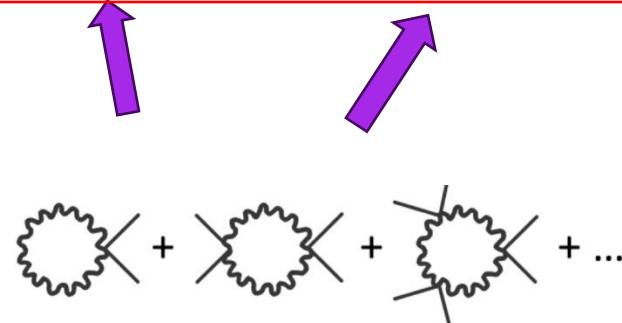
Image credit: Arthur Wu

New Scalar Field Effective Potential



$$V_{\text{eff}}(\phi, T) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi) + V_T(\phi, T)$$

$$\frac{1}{4}\lambda\phi^4$$

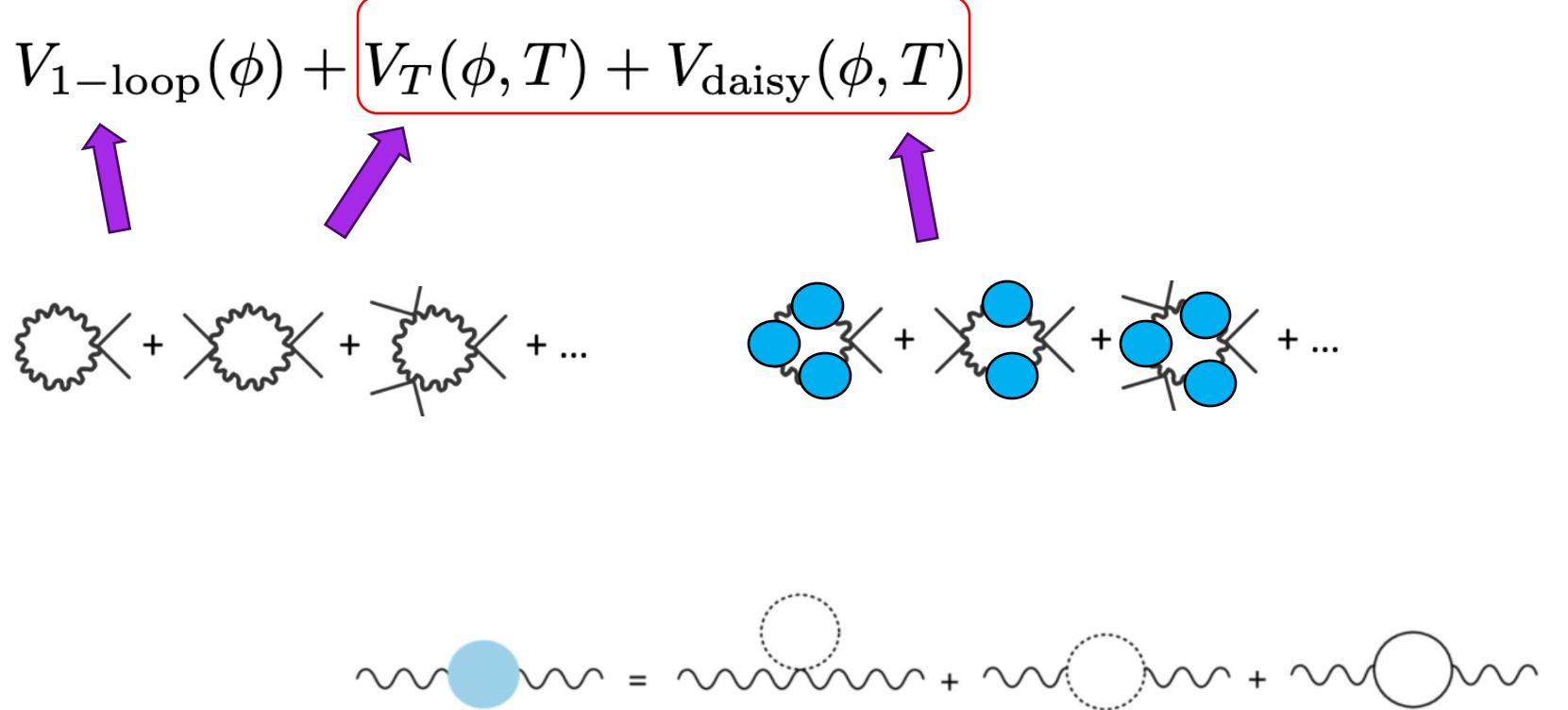


New Scalar Field Effective Potential



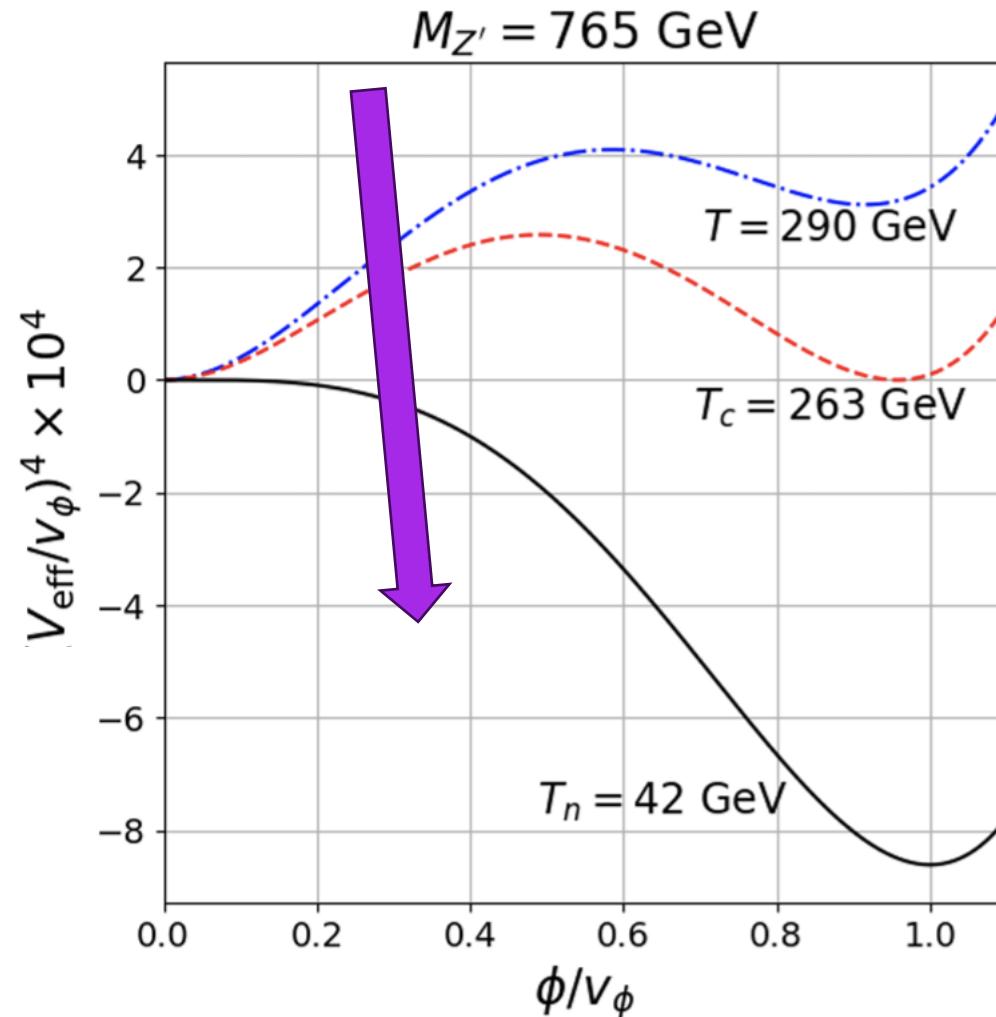
$$V_{\text{eff}}(\phi, T) = V_{\text{tree}}(\phi) + V_{1-\text{loop}}(\phi) + \boxed{V_T(\phi, T) + V_{\text{daisy}}(\phi, T)}$$

$$\frac{1}{4}\lambda\phi^4$$



arXiv:2009.02050

New Scalar Field Effective Potential



First Order Phase Transition

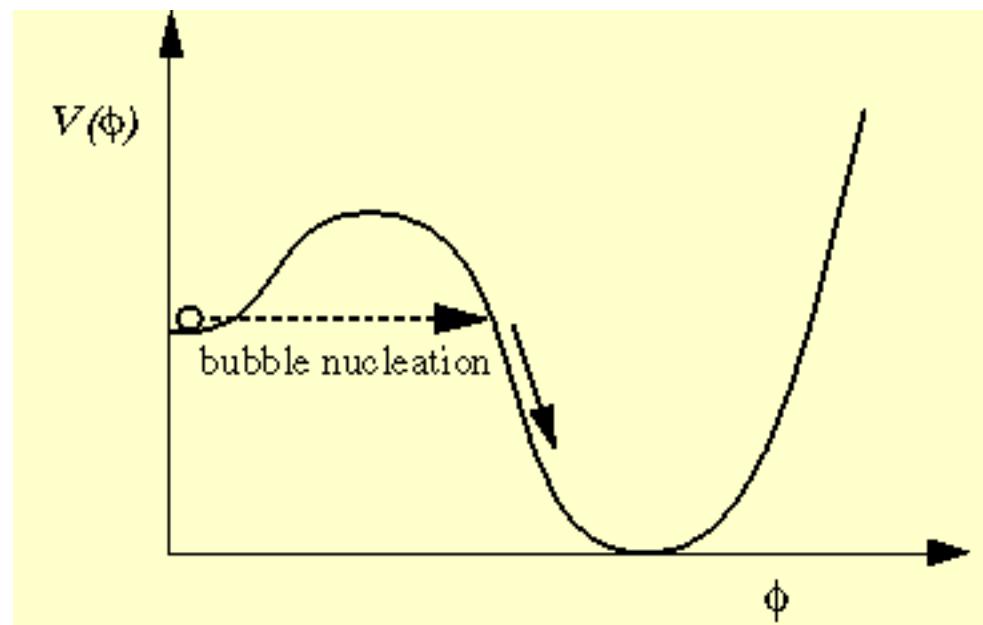


Image credit: Cambridge U

First Order Phase Transition

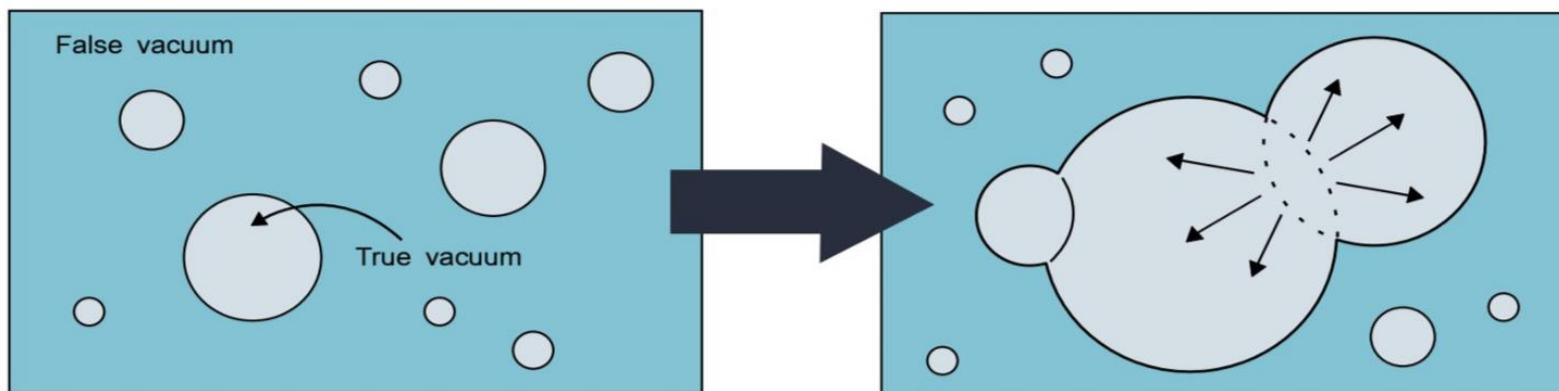
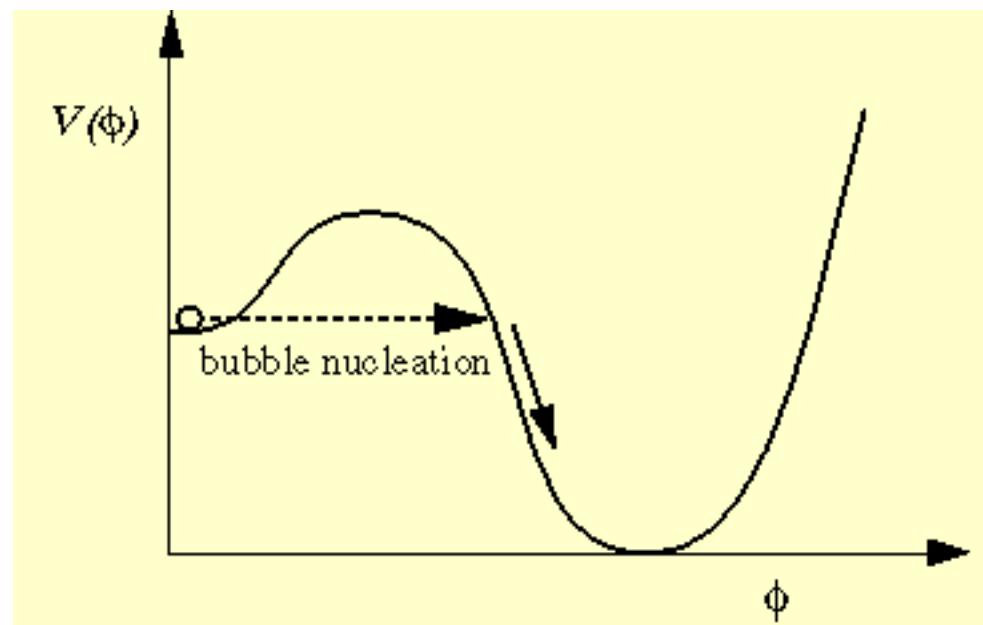


Image credit:
Giulio Barni

First Order Phase Transition



First Order Phase Transition

Bubble nucleation rate: $\Gamma(T) = [A(T)]^4 \exp[-S(T)]$

Nucleation Temperature when: $\frac{\Gamma(T)}{H(T)^4} \Big|_{T=T_n} = 1$

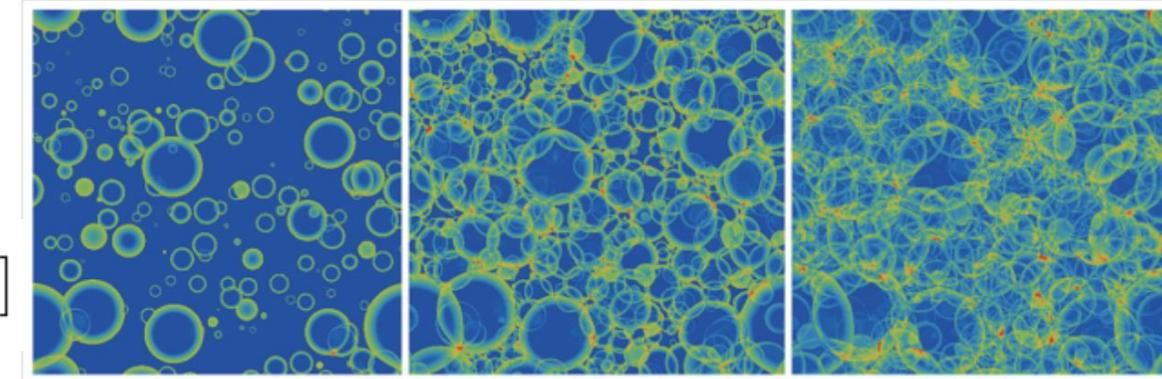
Vacuum energy density: $\alpha = \frac{1}{\rho_{\text{rad}}} \left(-1 + T \frac{d}{dT} \right) \Delta V_{\text{min}} \Big|_{T=T_*}$ (Transition temperature)

Inverse timescale:

$$\frac{\beta}{H_*} = - \frac{T}{\Gamma} \frac{d\Gamma}{dT} \Big|_{T=T_*}$$

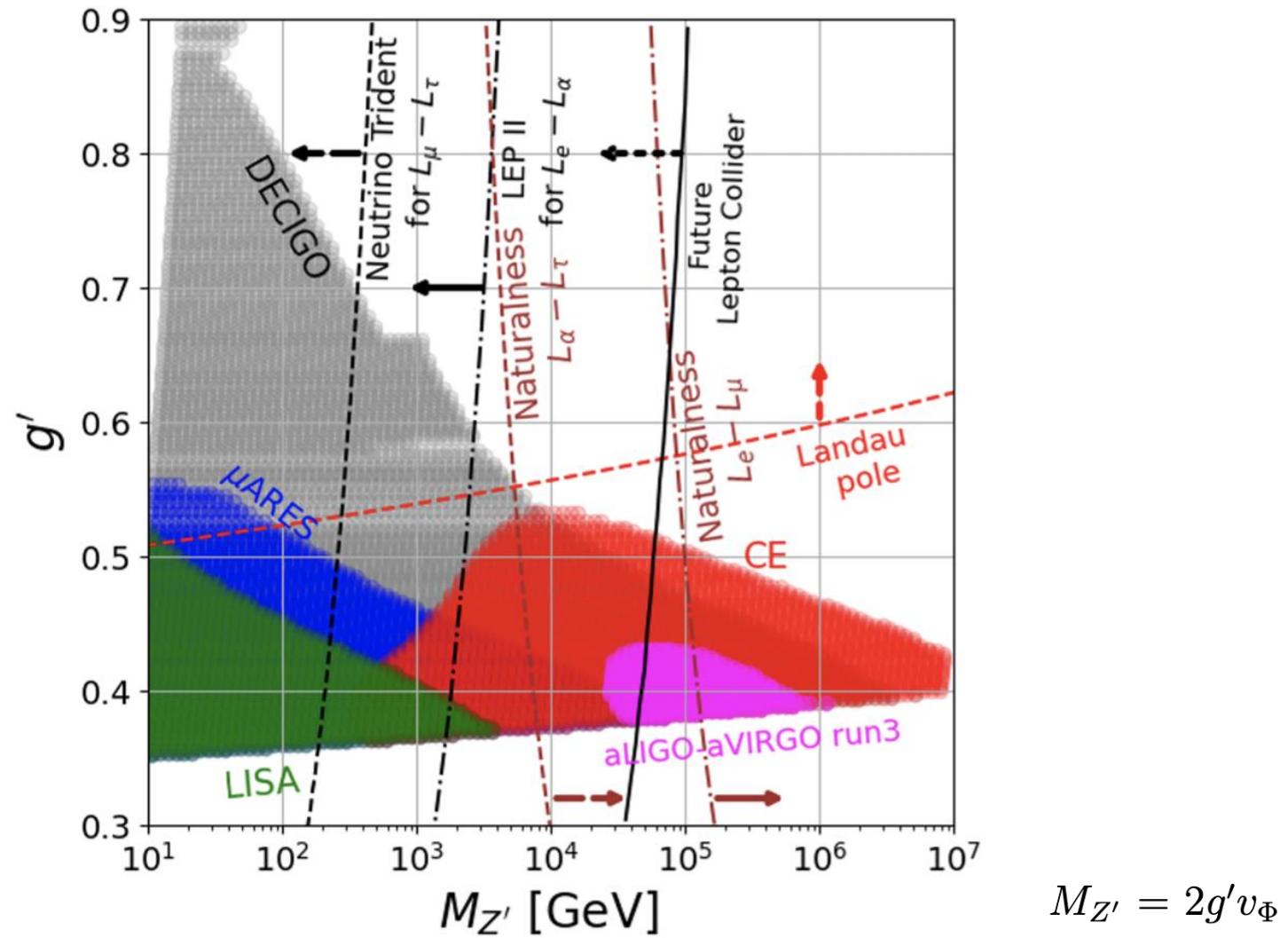
Bubble wall velocity: v_w

Gravitational Waves: $h^2 \Omega_{\text{GW}}(f) \simeq h^2 \Omega_b(f) + h^2 \Omega_s(f) + h^2 \Omega_t(f)$



Bubble nucleation Simulation of Higgs-bubble nucleation and expansion history during a first-order electroweak phase transition. Source: *JCAP* **04** 014

Gravitational Waves Constraints



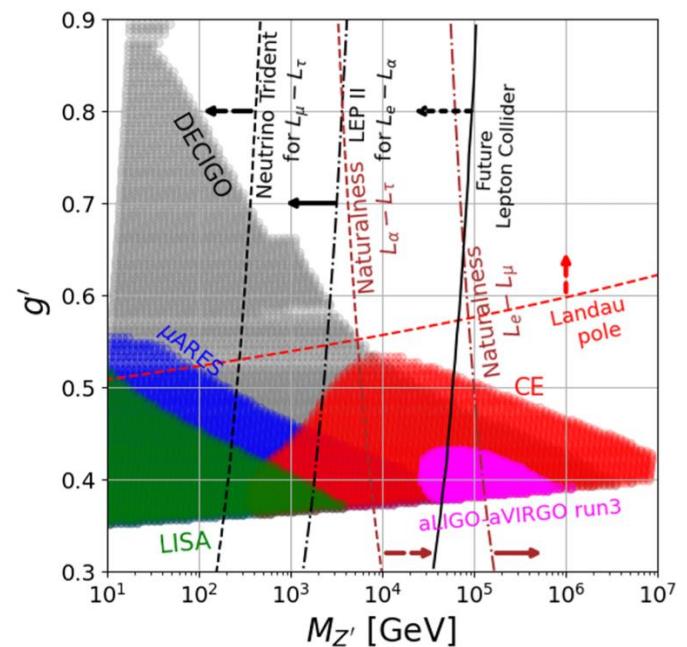
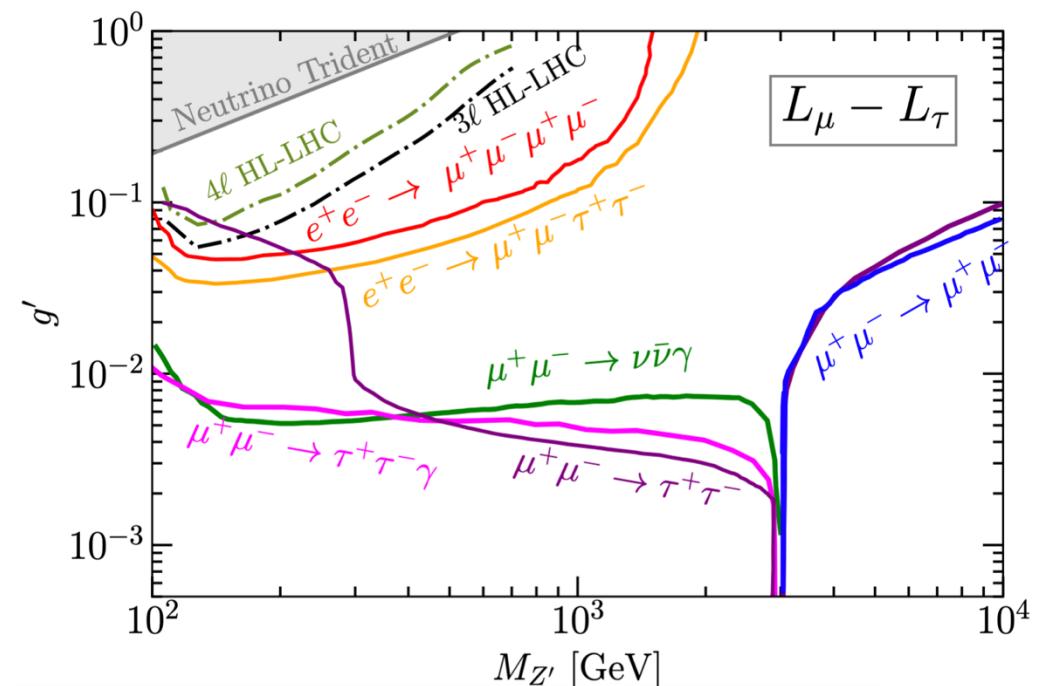
Summary

1. $SU(2)_L \times U(1)_Y \times U(1)'$

New particles:
gauge boson Z' and singlet scalar ϕ

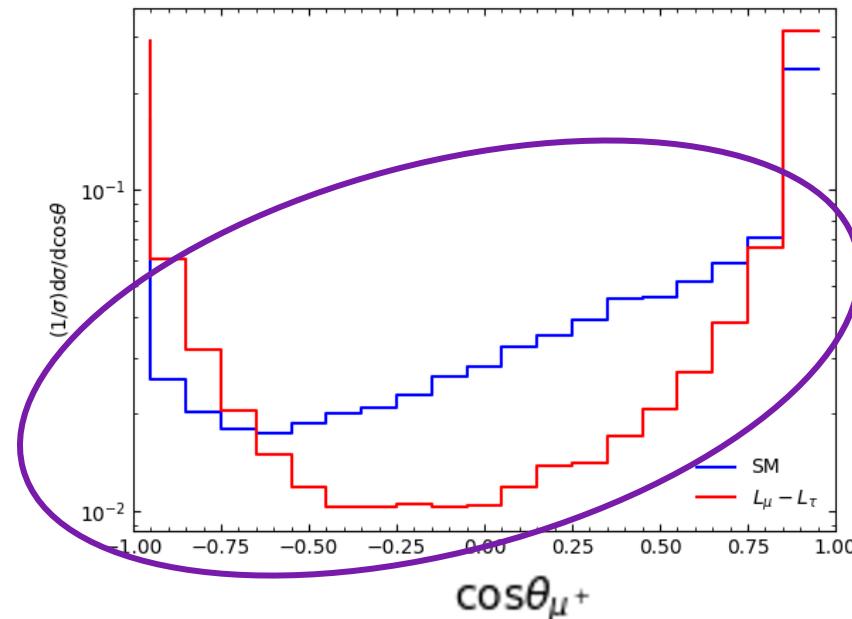
2. adding system rapidity cut
enhanced the sensitivity

3. Gravitational Waves can be
a complementary to the collider constraints



$\mu^+ \mu^- \rightarrow \tau^+ \tau^-$ with ISRFor $M_{Z'}$, 3 TeV to 10 TeV

$$\frac{S}{\sqrt{B}} = \frac{(\sigma_{Lmt} - \sigma_{SM})L}{\sqrt{\sigma_{SM}L}}$$



Chi square:

$$\chi^2 = \sum_i \frac{(N_i^{BSM} - \tilde{N}_i^{SM})^2}{\tilde{N}_i^{SM} + \epsilon^2 \tilde{N}_i^{SM2}}$$

 $\sqrt{s} = 3$ TeV $M_{Z'} = 500$ GeV $g' = 0.2$

$$\mathcal{L} = \mathcal{L}_{YM} + \mathcal{L}_s + \mathcal{L}_f + \mathcal{L}_Y .$$

1

$$\mathcal{L}_{YM}^{\text{Abel}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu},$$

$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu,$$

$$F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu.$$

2

$$\begin{aligned} \mathcal{L}_f = & \sum_{k=1}^3 \left(i\overline{q_{kL}}\gamma_\mu D^\mu q_{kL} + i\overline{u_{kR}}\gamma_\mu D^\mu u_{kR} + i\overline{d_{kR}}\gamma_\mu D^\mu d_{kR} + \right. \\ & \left. + i\overline{l_{kL}}\gamma_\mu D^\mu l_{kL} + i\overline{e_{kR}}\gamma_\mu D^\mu e_{kR} + i\overline{\nu_{kR}}\gamma_\mu D^\mu \nu_{kR} \right), \end{aligned}$$

$$D^\mu = \partial_\mu + ig_s T^\alpha G_\mu^\alpha + ig T^a W_\mu^a + ig_1 Y B_\mu + ig'_1 Y_{L_\mu - L_\tau} B'_\mu$$

3

$$\mathcal{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu \chi)^\dagger D_\mu \chi - V(H, \chi),$$

$$V(H, \chi) = m^2 H^\dagger H + \mu^2 |\chi|^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 |\chi|^4 + \lambda_3 H^\dagger H |\chi|^2,$$

4

$$\begin{aligned} \mathcal{L}_Y = & -y_{jk}^d \overline{q_{jL}} d_{kR} H - y_{jk}^u \overline{q_{jL}} u_{kR} \tilde{H} - y_{jk}^e \overline{l_{jL}} e_{kR} H \\ & - y_{jk}^r \overline{l_{jL}} \nu_{kR} \tilde{H} - y_{jk}^M \overline{(\nu_R)^c_j} \nu_{kR} \chi + \text{h.c.}, \end{aligned}$$

Anomaly Cancellation

For extra $U(1)'$ model, there are six anomaly-cancellation condition:

- (1) $SU(3)_C^2 \times U(1)'$, implies $\text{Tr}[\{\mathcal{T}^i, \mathcal{T}^j\}Y'] = 0$, which leads to $\sum_{colortriplets,i} Y'_i = 0$,
- (2) $SU(2)_L^2 \times U(1)'$, implies $\text{Tr}[\{T^i, T^j\}Y'] = 0$, which leads to $\sum_{isodoublets,i} Y'_i = 0$,
- (3) $U(1)_Y^2 \times U(1)'$, implies $\text{Tr}[Y^2 Y'] = 0$, which leads to $\sum_i Y_i^2 Y'_i = 0$,
- (4) $U(1)_Y \times U(1)^{'2}$, implies $\text{Tr}[YY'^2] = 0$, which leads to $\sum_i Y_i Y_i'^2 = 0$,
- (5) $U(1)^{'3}$, implies $\text{Tr}[Y'^3] = 0$, which leads to $\sum_i Y_i'^3 = 0$,
- (6) Gauge gravity, implies $\text{Tr}[Y'] = 0$, which leads to $\sum_i Y'_i = 0$

$$\begin{aligned} & Y'_{eR} + Y'_{\mu R} + Y'_{\tau R} + 2(Y'_{eL} + Y'_{\mu L} + Y'_{\tau L}) \\ & + 3 * 2(Y'_{uL} + Y'_{cL} + Y'_{tL}) + 3 * 2(Y'_{uR} + Y'_{cR} + Y'_{tR}) = 0 \end{aligned}$$

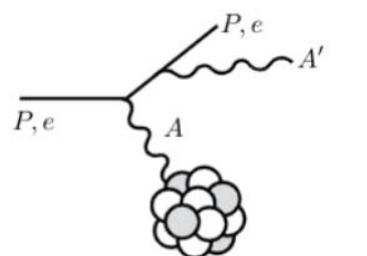
Current Constraints

[M. Bauer, P. Foldenauer, J. Jaeckel(2018)]

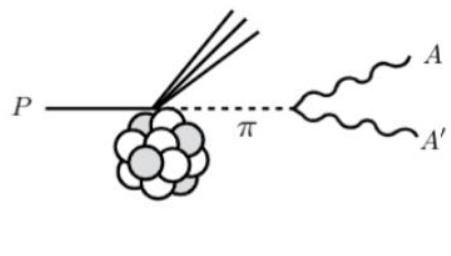
Mass region: MeV-100 GeV

1. Beam dump experiments & fixed target experiments

(SLAC E137, Fermilab E774, Orsay; SHiP...)



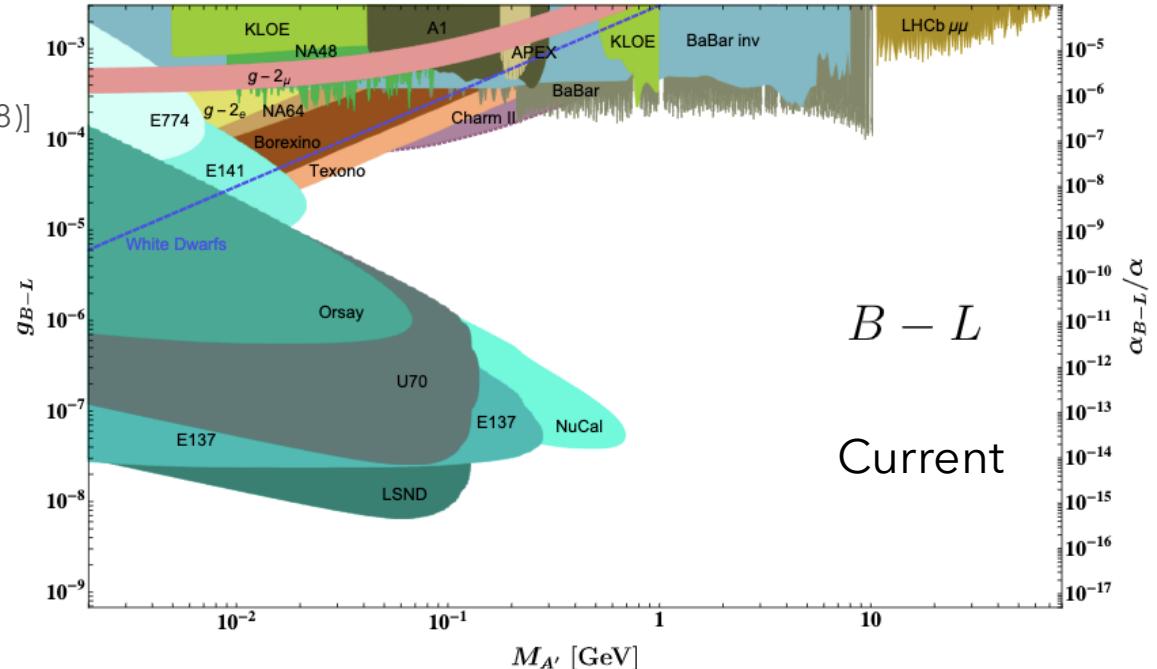
Bremsstrahlung



meson production

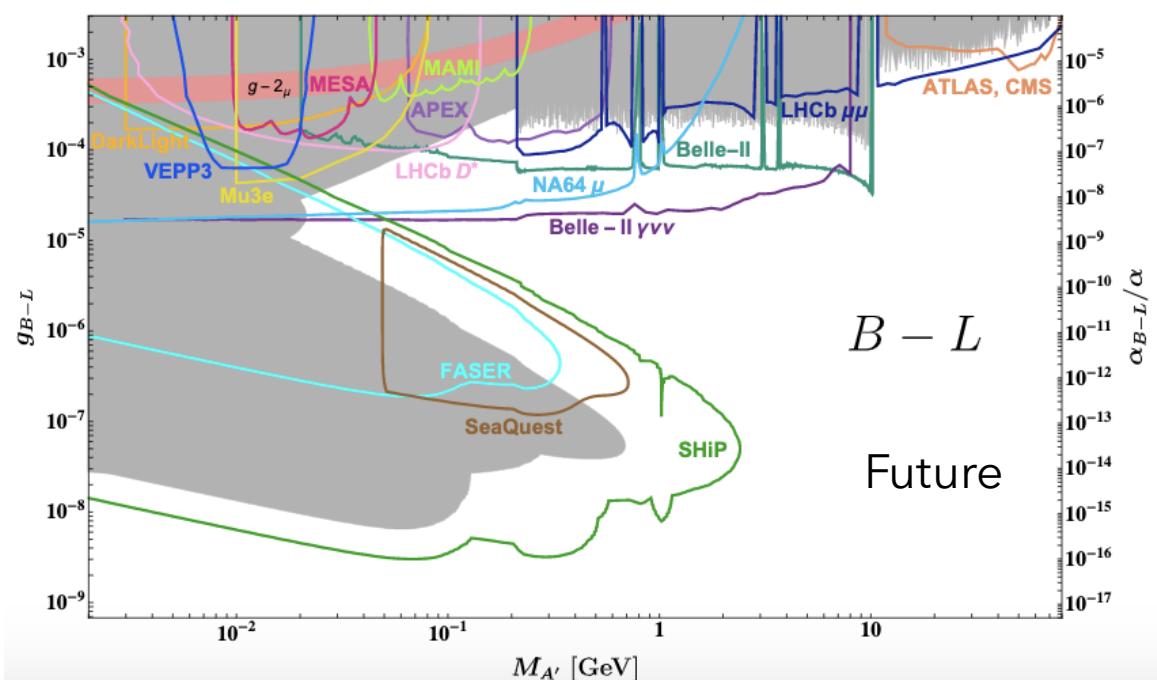
2. Neutrino Experiments

(COHERENT, Charm-II, Texono...)



$B - L$

Current



$B - L$

Future

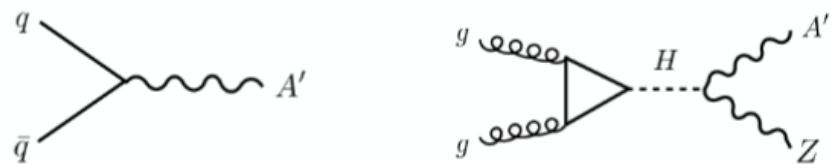
Current Constraints

[M. Bauer, P. Foldenauer, J. Jaeckel(2018)]

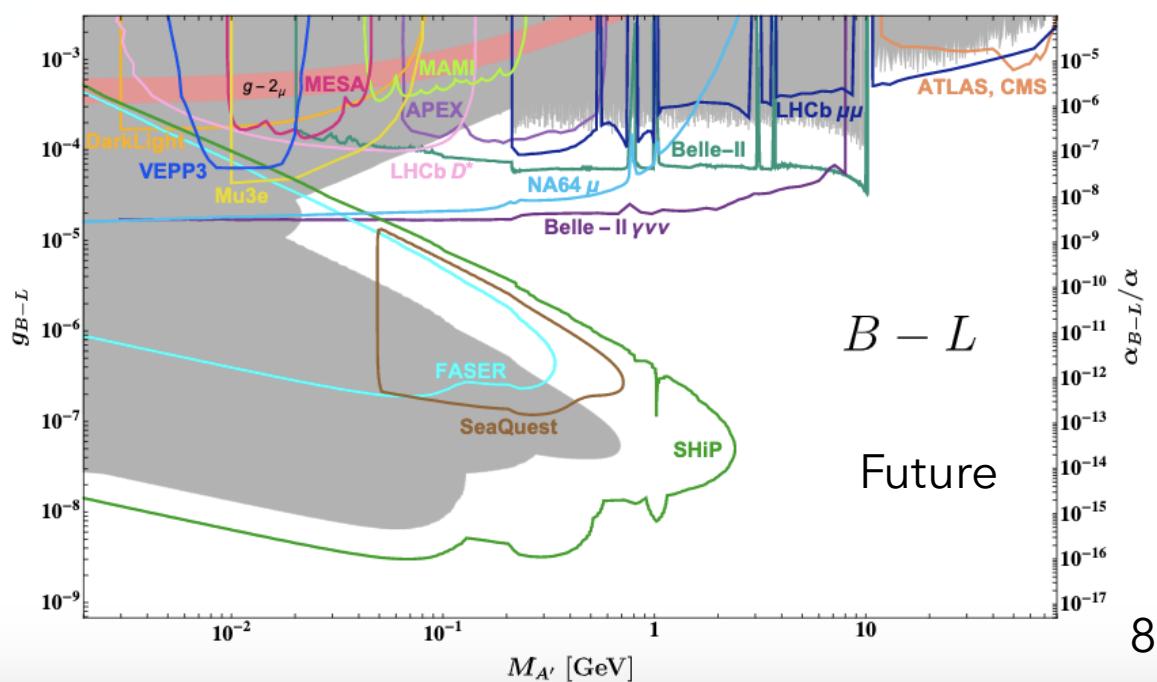
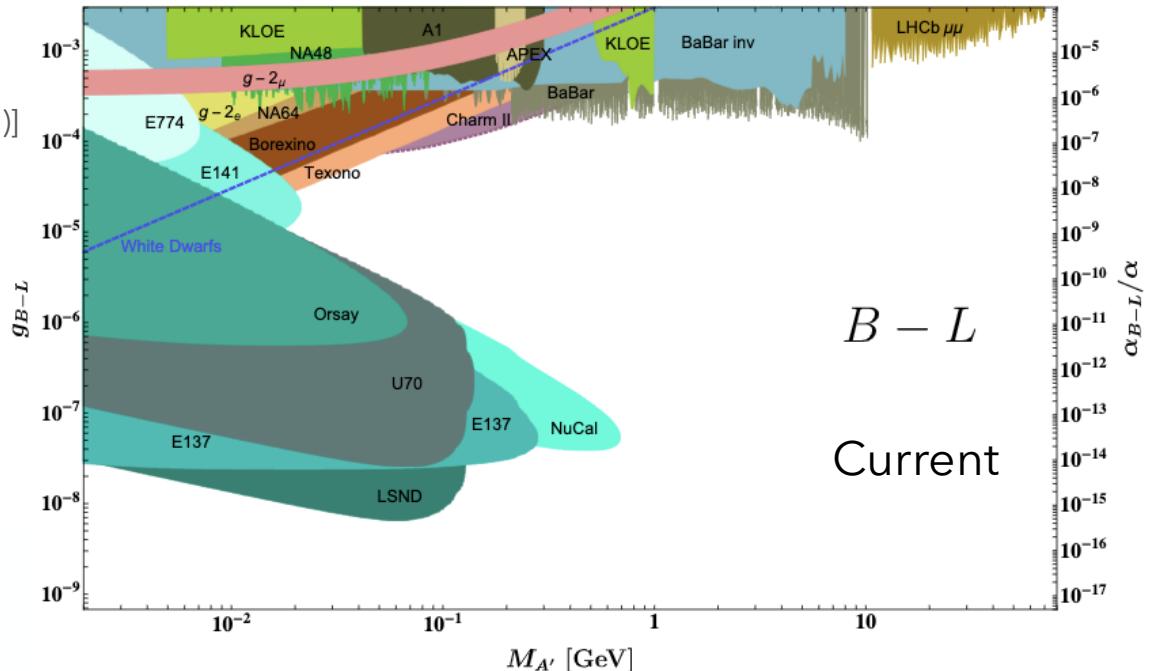
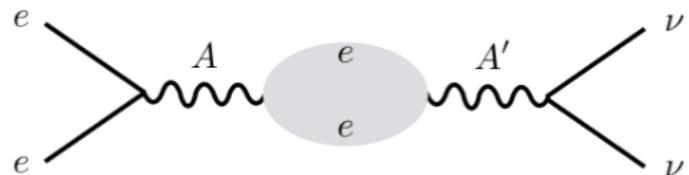
Mass region: MeV-100 GeV

3. Collider Experiments

(ATLAS, CMS, LHCb, BaBar, KLOE...)

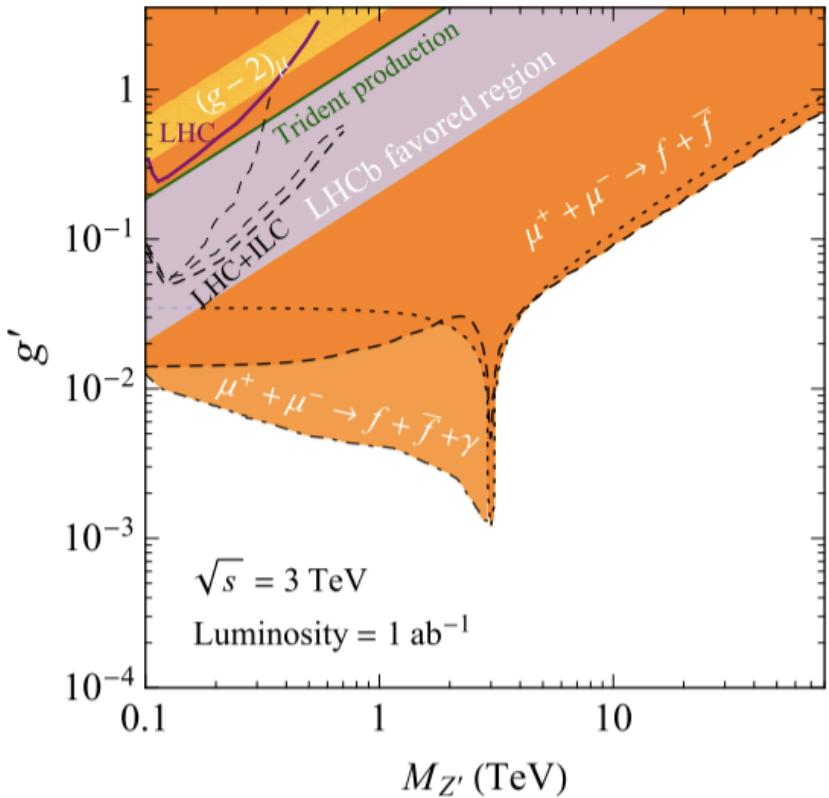


4. White Dwarf Cooling

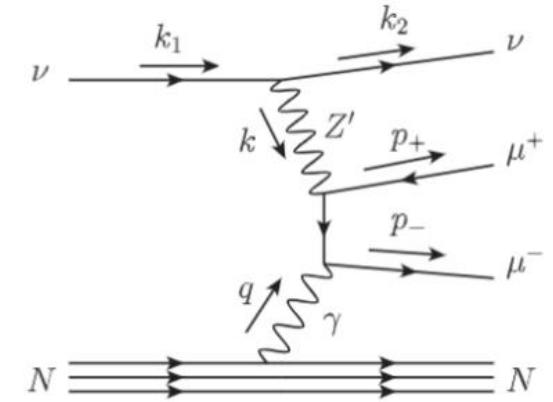


Current Constraints

Mass region: 0.1 TeV to 100 TeV



Neutrino Trident Experiment:



$$\sigma_{CCFR}/\sigma_{SM} = 0.82 \pm 0.28$$

$$\frac{\sigma_{SM+Z'}}{\sigma_{SM}} = \frac{1 + (1 + 4s_W^2 + 2v^2 q_l^2 (g')^2 / M_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}$$

$$M_{Z'} > 540 \text{ GeV} \times g'$$

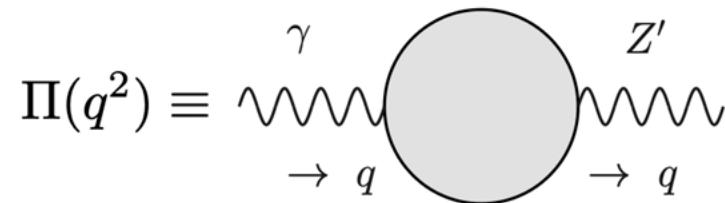
[G. Huang, F.S. Queiroz, W. Rodejohann(2021)]

should consider VBF background

Z-Z' Mixing

Mixing term

$$\mathcal{L}_{\text{mix}} = -\epsilon Z'^{\mu\nu} B_{\mu\nu} + \delta M^2 Z'^{\mu} Z_{\mu}$$



$$= \frac{8eg'}{16\pi^2} \int_0^1 dx \ x(1-x) \log \left[\frac{m_{\ell_\beta}^2 - x(1-x)q^2}{m_{\ell_\alpha}^2 - x(1-x)q^2} \right]$$

Z' Particle Width

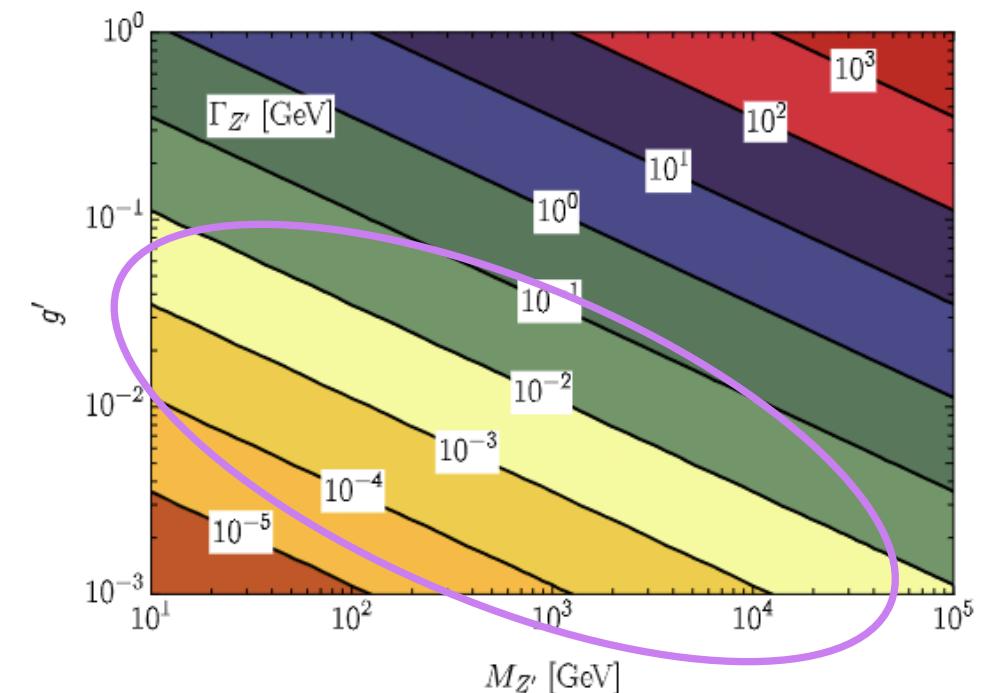
No RH LH difference

Width: $\mathcal{M} = -g'\epsilon^\mu \bar{u}(p_1) \gamma_\mu v(p_2)$

$$\Gamma = \frac{g'^2 M_{Z'}}{12\pi}$$

$$\Gamma(Z' \rightarrow l\bar{l}) = 2\Gamma(Z' \rightarrow \nu\bar{\nu})$$

$$\boxed{\Gamma_{tot} = \frac{(2N_l + N_\nu)g'^2}{24\pi} M_{Z'}} = \frac{6g'^2}{24\pi} M_{Z'}$$



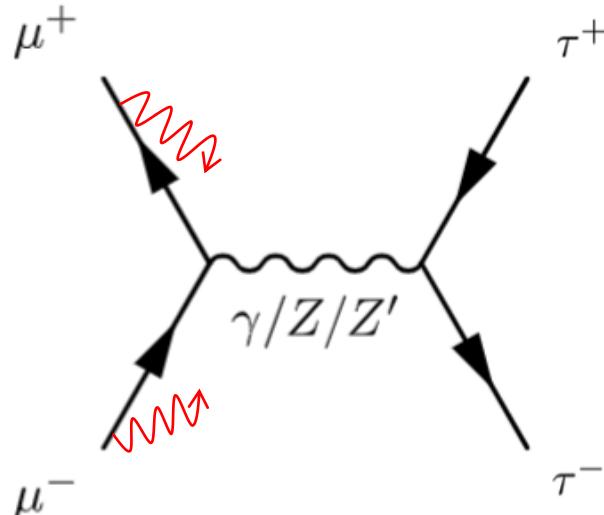
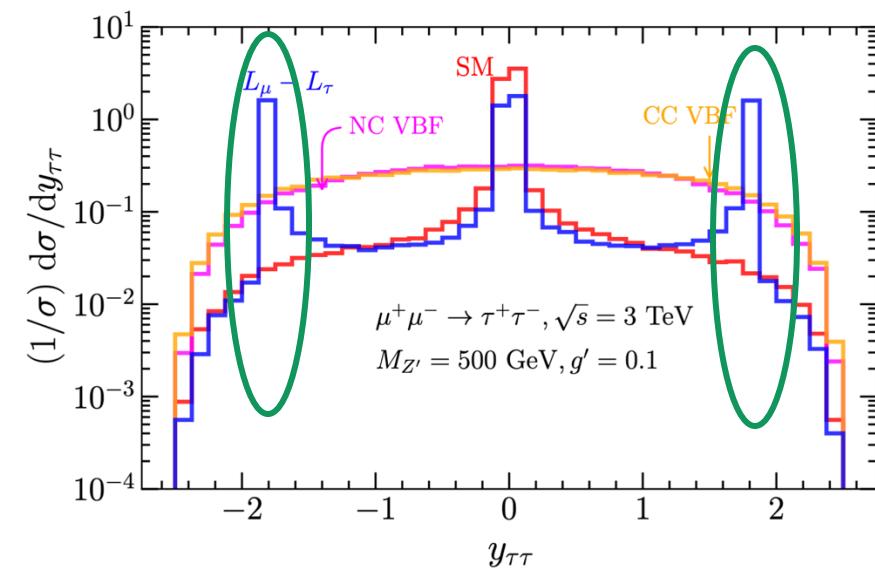
Ignore lepton masses

$$c\tau = \frac{c}{\Gamma(Z')} = 2.48 \times 10^{-4} \mu m \left(\frac{10^{-3}}{g'} \right)^2 \left(\frac{10 \text{ GeV}}{M_{Z'}} \right)$$

Prompt decay

On-Shell Z' Particle Production

System Rapidity Cut



$$P_{Z'} = P_{\mu^+} + P_{\mu^-}$$

$$= \left(\frac{1}{2}\sqrt{s} - E_\gamma, \frac{1}{2}\sqrt{s} - E_\gamma \right) + \left(\frac{1}{2}\sqrt{s}, -\frac{1}{2}\sqrt{s} \right) = (\sqrt{s} - E_\gamma, -E_\gamma)$$

$$M_{Z'}^2 = P_{Z'}^2 = (\sqrt{s} - E_\gamma)^2 - E_\gamma^2 = s - 2\sqrt{s}E_\gamma$$

(the energy-momentum relation)

$$E_\gamma = (s - M_{Z'}^2)/2\sqrt{s}$$

$$y_{Z'} = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} = \frac{1}{2} \ln \frac{\sqrt{s} - 2E_\gamma}{\sqrt{s}} = \boxed{\frac{1}{2} \ln \frac{M_{Z'}^2}{s}}$$

$$y_{Z'} \approx \log \cot(\theta/2) \rightarrow \tan(\theta/2) \approx M_{Z'}/\sqrt{s}$$

$$|\eta_\ell| < 2.44$$

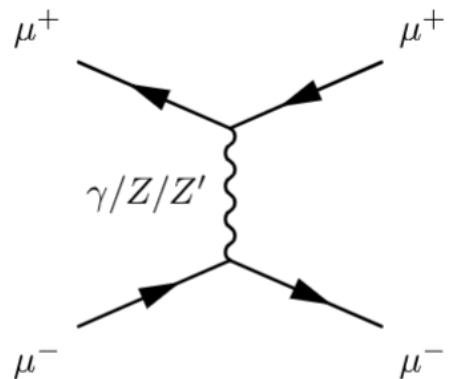
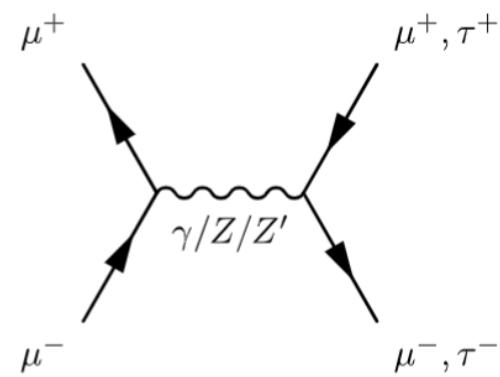
$$\boxed{M < 0.088\sqrt{s}}$$

(momentum conservation)

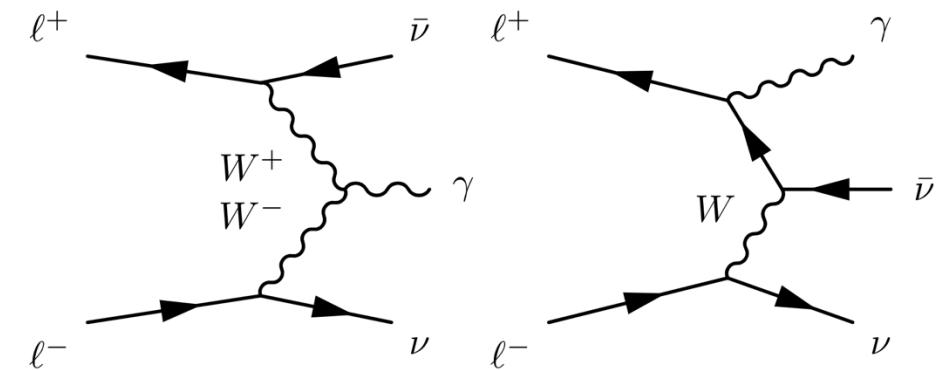
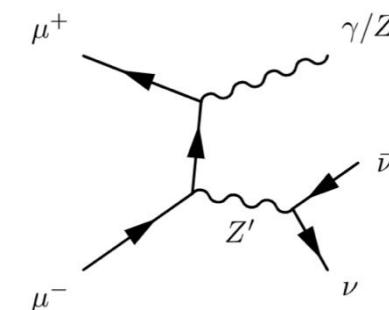


Directly Coupled to Z' Particle

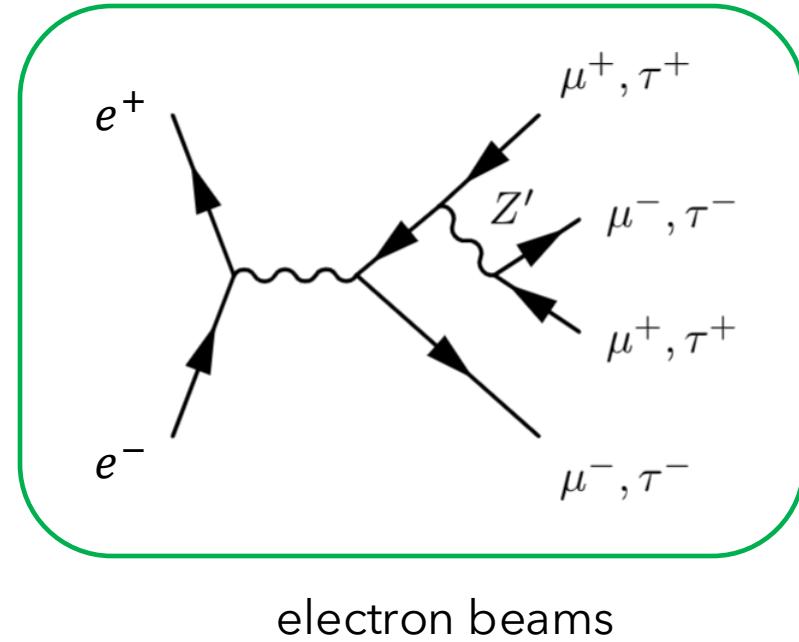
$$\mu^+ \mu^- \rightarrow \mu^+ \mu^-$$



$$\mu^+ \mu^- \rightarrow \tau^+ \tau^- \gamma \text{ (Mono Photon)}$$



Indirectly Coupled to Z' Particle



Back Up

- B-L

$$\mathcal{L} = \mathcal{L}_{YM} + \mathcal{L}_s + \mathcal{L}_f + \mathcal{L}_Y .$$

$$\begin{aligned}\mathcal{L}_{YM}^{\text{Abel}} &= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu}-\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}, & F_{\mu\nu} &= \partial_\mu B_\nu-\partial_\nu B_\mu, \\ & & F'_{\mu\nu} &= \partial_\mu B'_\nu-\partial_\nu B'_\mu.\end{aligned}$$

$$D_\mu \equiv \partial_\mu + i g_S T^\alpha G_\mu{}^\alpha + i g T^a W_\mu{}^a + i g_1 Y B_\mu + i g'_1 Y_{B-L} B'_\mu \,.$$

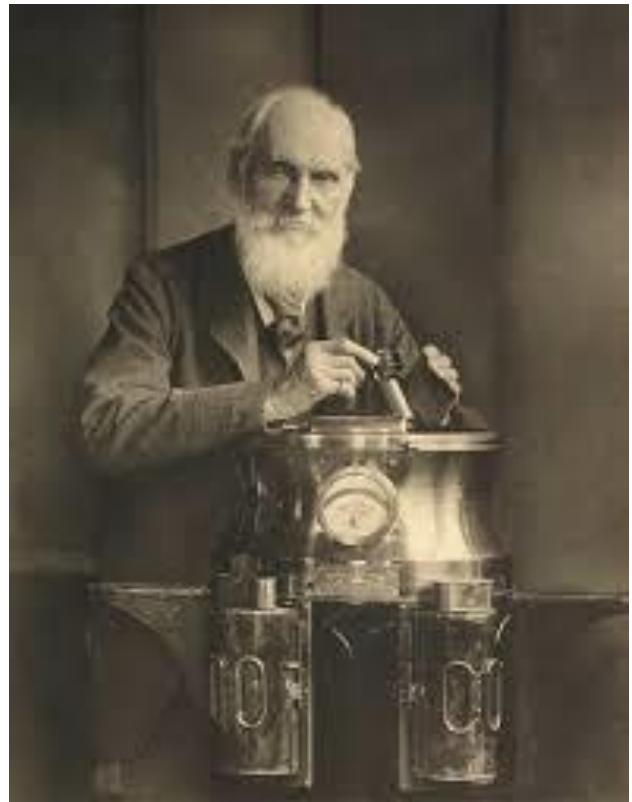
$$\begin{aligned}\mathcal{L}_f &= \sum_{k=1}^3 \left(i\overline{q_{kL}}\gamma_\mu D^\mu q_{kL} + i\overline{u_{kR}}\gamma_\mu D^\mu u_{kR} + i\overline{d_{kR}}\gamma_\mu D^\mu d_{kR} + \right. \\ &\quad \left. + i\overline{l_{kL}}\gamma_\mu D^\mu l_{kL} + i\overline{e_{kR}}\gamma_\mu D^\mu e_{kR} + i\overline{\nu_{kR}}\gamma_\mu D^\mu \nu_{kR} \right),\end{aligned}$$

$$\mathcal{L}_s = (D^\mu H)^\dagger D_\mu H + (D^\mu \chi)^\dagger D_\mu \chi - V(H, \chi),$$

$$V(H,\chi)=m^2H^\dagger H+\mu^2\mid\chi\mid^2+\lambda_1(H^\dagger H)^2+\lambda_2\mid\chi\mid^4+\lambda_3H^\dagger H\mid\chi\mid^2,$$

$$\begin{aligned}\mathcal{L}_Y &= -y_{jk}^d\overline{q_{jL}}d_{kR}H-y_{jk}^u\overline{q_{jL}}u_{kR}\widetilde{H}-y_{jk}^e\overline{l_{jL}}e_{kR}H \\ &\quad -y_{jk}^\nu\overline{l_{jL}}\nu_{kR}\widetilde{H}-y_{jk}^M\overline{(\nu_R)_j^c}\nu_{kR}\chi+\text{h.c.},\end{aligned}$$

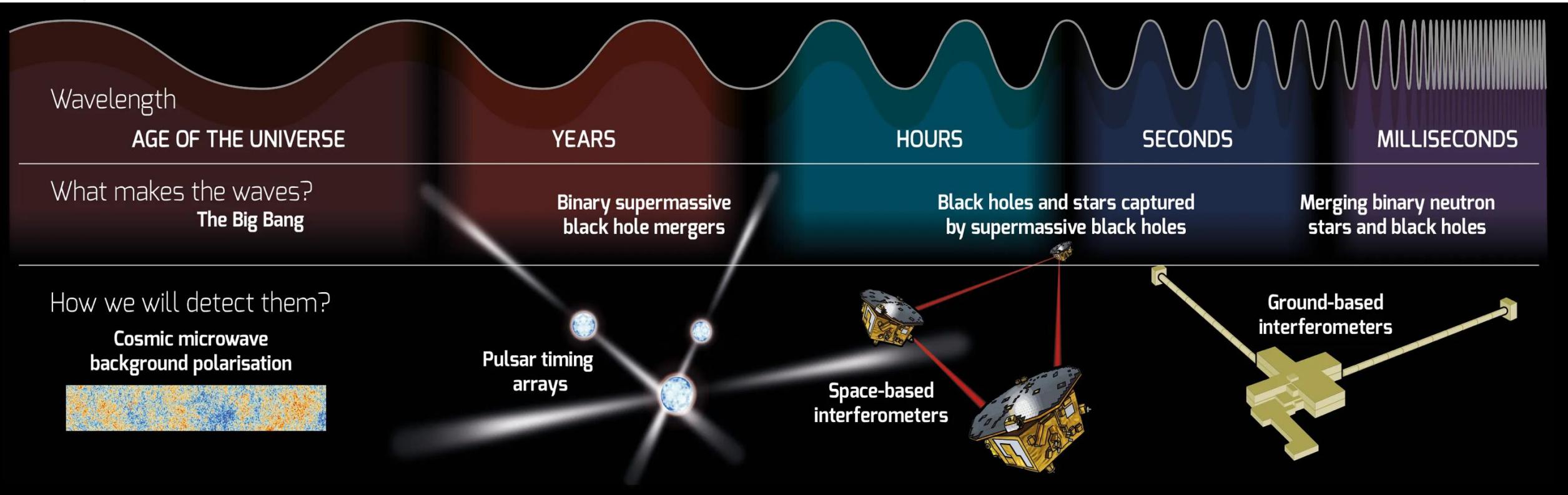
Why are Atoms so Small?



Suppose that you could mark the molecules in a glass of water; then pour the contents of the glass into the ocean and stir the latter thoroughly so as to distribute the marked molecules uniformly throughout the seven seas; if then you took a glass of water anywhere out of the ocean, you would find in it about a hundred of your marked molecules.

Lord Kelvin

The Gravitational Waves Spectrum



SKA

IPTA

LISA

Advanced LIGO
+
Virgo